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SUPERPLASTIC FORMED ALUMINUM AIRFRAME STRUCTURES
VOLUME I - EXECUTIVE SUMMARY

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This report summarizes the work done on Contract F33615-81-C-3227, "Superplastic Formed Aluminum Airframe Structures." The scope of this program was to select, design, fabricate, evaluate, and test superplastically formed (SPF) aluminum airframe Parts. The program was conducted in the following five tasks:

In Task I several candidate structural components were evaluated for SPF production design, and two parts, namely, Leading Edge Extension (LEX) and avionics deck compartment, showing the most benefits from SPF, were selected.

Task II dealt with selection of suitable alloy for fabrication of structural components. After a detailed evaluation, Reynold's aluminum alloy MD254 was selected for part fabrication. (SES)

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11. Superplastic Formed Aluminum Airframe Structures (Executive), Volume I

19. ABSTRACT (Continued)

In Task III, subcomponents, which represented the most severe forming areas of each component were fabricated and tested. The selected subcomponents represented the critical forming areas of the full-scale components.

Task IV involved fabricating and assembling the avionics deck. In addition, corrugations for the LEX were superplastically formed.

Part evaluation and structural verification were carried out in Task V. Structural verification involved static and fatigue tests of the avionics deck compartment.

The studies carried out in this program have shown that complex aluminum structural parts can be superplastically formed, resulting in substantial cost and weight savings.

PREFACE

This report was prepared by the Northrop Corporation, Aircraft Division, Hawthorne, California, covering work done under the United States Air Force Contract F33615-81-C-3227 between November 1981 and July 1986. The contract was administered by the Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. J. Tuss was the AFWAL/FIBCB Project Engineer from November 1981 to November 1985 and Mr. R. Rolfes from November 1985 to July 1986.

The work was performed in the Northrop Advanced Structural Concepts Department under the program management of Mr. L. Bernhardt from November 1981 to July 1984 and Dr. M. M. Ratwani from August 1984 to July 1986. Mr. H. Zamani was the Principal Investigator on this program. The following Northrop personnel were the major contributors to the program:

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INTRODUCTION

Superplastic forming (SPF) is one of the most important technologies recently developed. Superplasticity is a unique property, exhibited by certain alloys having a characteristic microstructure, by which alloys undergo large uniform elongations without fracture when subjected to appropriate temperature and forming strain rates. This unique property makes it possible to form parts with much tighter radii and complex shapes.

The use of SPF technology in fabrication of fighter structures offer several advantages. The main advantage is the reduction in piece count. The SPF process combines many separate parts into one monolithic structure, thus reducing the number of details, fasteners, and costs associated with materials, fabrication, assembly, tooling and inspection. In addition, installation, maintenance and labor hours are greatly reduced. Lighter weight also results from a reduction in the overlapping areas of individual pieces.

Another major advantage of SPF is the elimination of "springback". Conventionally formed parts have significant residual stresses and tend to form back to their original shape upon the removal of forming pressures. SPF parts have minimal residual stresses and consequently less tendency for springback. This reduced springback results in closer tolerances which could be advantageous during the assembly of SPF parts.

1.1 BACKGROUND

The bulk of SPF development work in the past has concentrated on superplastic forming of titanium. Superplastic forming of titanium has demonstrated significant cost and weight savings for selected structural airframe parts. A number of SPF titanium parts are being used in production aircraft. The successful applications of SPF titanium technology to aircraft structures led to exploring the SPF potential of aluminum. Initial explorations of SPF in 7000-series aluminum alloys showed considerable promise. Air Force Contract No. F33615-79-C-3218 (Reference 1) demonstrated that high strength aluminum alloys, such as 7075 and 7475, have SPF potential after their wrought forms have undergone grain refinement. The grain refinement is achieved through a thermomechanical process that produces grain size in the 9-μm to 15-μm range. This grain size enables the material to undergo tensile elongations of about 400 percent in the 850 to 900°F range. We feel that other alloys, including powder aluminum alloys, have the potential to provide valuable cost and weight savings through superplastic forming.

The feasibility to produce SPF aluminum full scale structural airframe parts has been successfully demonstrated on Air Force Contract No. F33615-80-C-3240 (Reference 2). The cost and weight savings, with the quality of the parts produced, demonstrated the valuable potential of the SPF aluminum process.

1.2 OBJECTIVE

The objective of this program was to exploit and develop applications of SPF aluminum and demonstrate the process as a viable means of producing structural airframe parts that are more cost effective than conventionally produced parts. Several aluminum alloys were evaluated for their SPF potential and the best one selected for further evaluation and final component fabrication. The structural integrity of the part(s) was then demonstrated by structural testing.

1.3 SCOPE

The scope of this program was to select, design, fabricate, evaluate and test SPF aluminum structural airframe parts. The SPF parts were to be designed as replacements for baseline components on an existing vehicle. The Air Force was provided with a full scale SPF aluminum demonstration airframe component that was evaluated and tested for its structural integrity. The program was divided into five tasks with the following specific objectives.

Task I - Part Selection & Design

From the results of design/producibility trade studies on several candidate structural components, production SPF designs were developed for two components showing the most benefits. Additionally, preliminary design criteria, material procurement, and process specification documents were drawn up. A subcomponent test plan for each selected component was formulated.

Task II - Material Selection and Evaluation

From the results of a preliminary evaluation of three aluminum alloys thermomechanically treated to optimize superplasticity, one alloy was chosen for extensive evaluation and fabrication of the structural components. This task was to run concurrently with Task I.

Task III - Producibility Forming Tests

Subcomponents which represented the most severe forming areas of each component were fabricated and tested. The selected subcomponents were to have various cross sections which simulated critical forming areas of the full scale parts.

Task IV - Part Fabrication

A full scale SPF component was fabricated and assembled in this task.

Task V - Part Evaluation and Structural Verification

The full scale SPF part was examined for its forming quality and tested for structural integrity.

SECTION 2

PART SELECTION AND DESIGN

This task involved the selection and design of two candidate SPF components. The selected parts would utilize the unique capabilities of the SPF process to provide significant cost and weight savings. The selected parts were designed as replacements for baseline components on an existing vehicle. The selection of the parts and their design is discussed in the following subsections.

2.1 PARTS SELECTION

The Northrop F-5E/F aircraft was selected as the baseline aircraft for this program. The F-5E/F fuselage is of conventional frame and longeron construction. Secondary structures such as doors, fairings, etc., are a combination of waffle pans or honeycomb construction. Therefore, any structural component selected from the F-5E/F would be an excellent generic example of fighter aircraft structure. A number of candidate parts representing both primary and secondary structures were considered. Obvious areas of potential payoff were applications where labor intensive subassemblies, extensive machining and corresponding material wastage could be eliminated. Also, the selected parts were to be produced from sheet material and designed to meet all service life loading and if applicable, fatigue loading requirements of their respective baseline components.

2.1.1 Conceptual Design Studies

Conceptual design studies involved a redesign of the selected components as SPF assemblies. The major emphasis was on reduction of piece count and assembly costs. Four candidate structural assemblies were selected for preliminary evaluation, representing the most advantageous application of superplastic forming on the F-5E/F aircraft. Structural descriptions of these four assemblies are given below.

CONCEPT 1 - Forward Avionics Deck

As shown in Figure 1, the original assembly was comprised of a six-part split-level deck supported by eight frame segments and six beam segments, with their adjacent shear webs joined by separate shear clips. This structure is bounded by two machined bulkheads and left and right hand longerons which join the deck to the outer skin providing lands for the avionics compartment access door. The part count breakdown is as follows: 21 stretch-formed extrusions, 39 hydroformed sheet metal details, 2 flat sheet decks, and 1 stretch-formed outer skin, totaling 63 parts in all.

The original SPF assembly, Figure 1, was designed around five pieces, two of which were common to the original design. All of the substructure was combined into one waffle pan. The upper deck was a one-piece pan. The outer skin was superplastically formed in a two-piece thermoform die. A waffle pattern insert and outer skin shim were added to the die so the waffle pan could be formed. Additional inserts and waffle pan shims were added to the die so the inner deck pan could be formed. Where necessary, multiple sheets were formed on both the waffle pan and inner skin to provide required doublers. All the necessary parts were formed in one segmented die assuring proper fitup for the subsequent assemblies. The design was subsequently modified based on the results of forming producibility tests. The details of modification are discussed in Volume II (Reference 3).

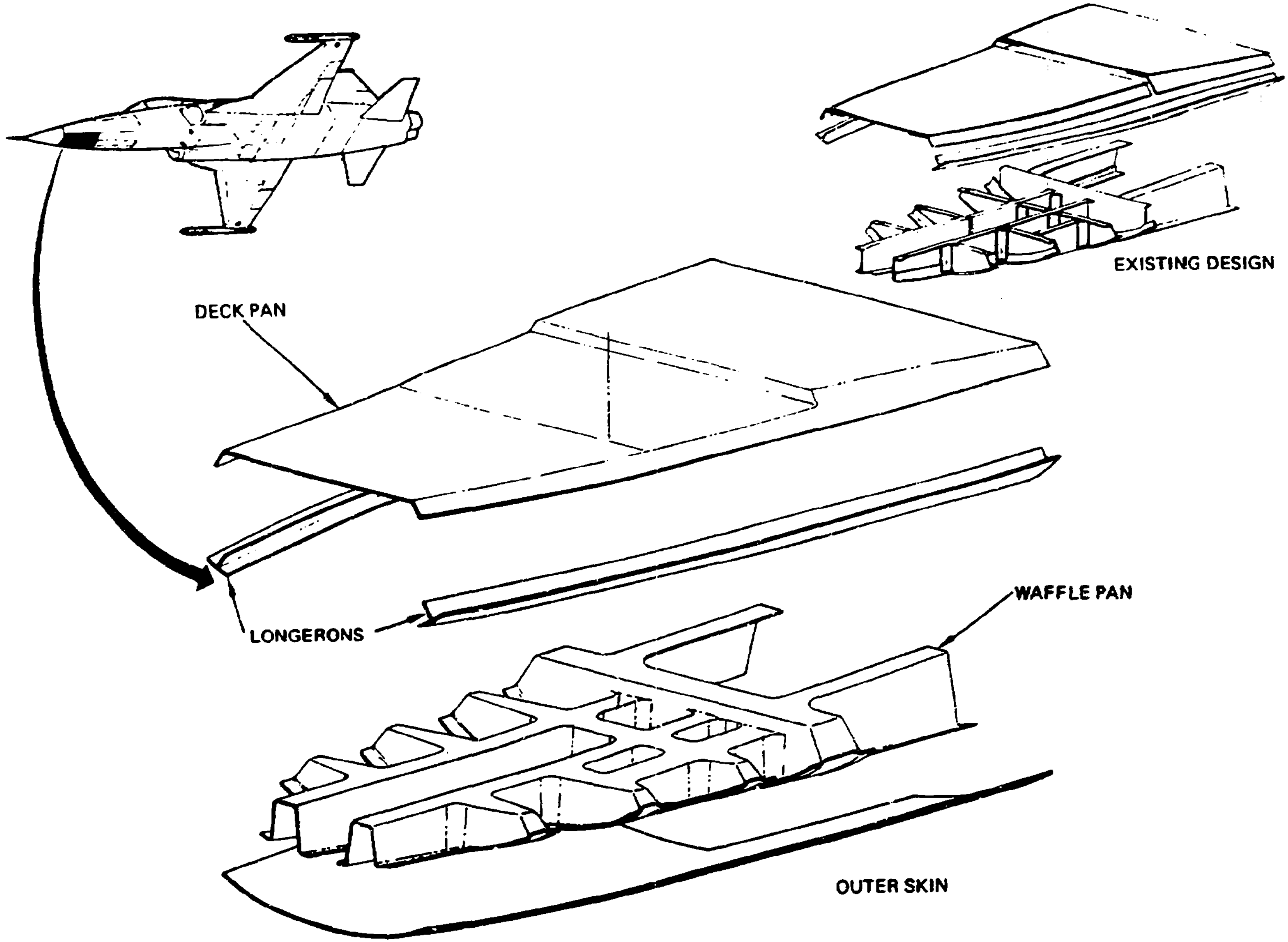

Figure 1. Baseline and SPF F-5F lower Avionics Deck

The final SPF assembly was made from only ten pieces. All of the substructure was combined into one waffled pan (four formers and three intercostals. The final assembly was rivet bonded and cured in an oven.

CONCEPT 2 - Nose Gear Wheel Door

The original design is a simple honeycomb stiffened pre-warped door supported on two hinges and articulated by an actuator attached to the left hand forward corner (Figure 2). The design is complicated by a cooling air outlet vent located in the center of the door.

The SPF design (Figure 2) substituted a ribbed pan for the honeycomb core and integrates several vent pieces into the door skin and inner pan. This design is an all bonded assembly.

The outer skin, the ribbed stiffening pan and the louver stiffener would be superplastically formed. The three doublers, the fairing, and the louver inner surface would be formed conventionally. Also, there are two machined aluminum backup ribs at the hinge locations to provide hinge support and transverse stiffness.

CONCEPT 3 - Trailing Edge Flap

The original design (Figure 3) of the trailing edge flap consists of ten, two-piece ribs equally spaced along a main spar at the 77 percent chord plane. There are also leading and trailing edge spars, the latter being a closeout member for the separate bonded honeycomb trailing edge assembly. The two inboard most ribs are actually double ribs, strengthened to accept the concentrated loads introduced by the inboard hinge and actuator fittings. The outboard hinge support rib is a machined fitting.

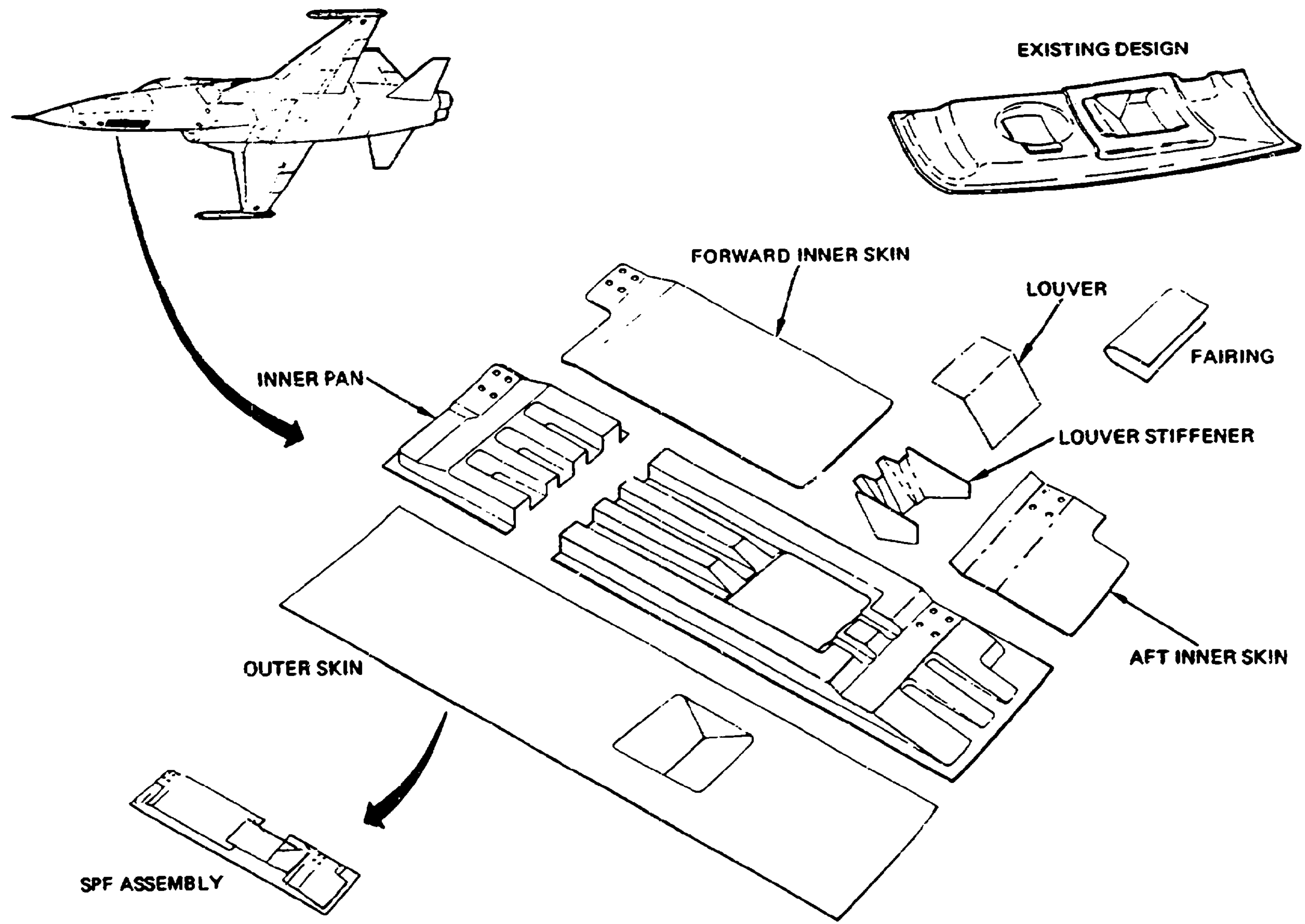

Figure 2. Baseline and SPF Nose Gear Wheel Door

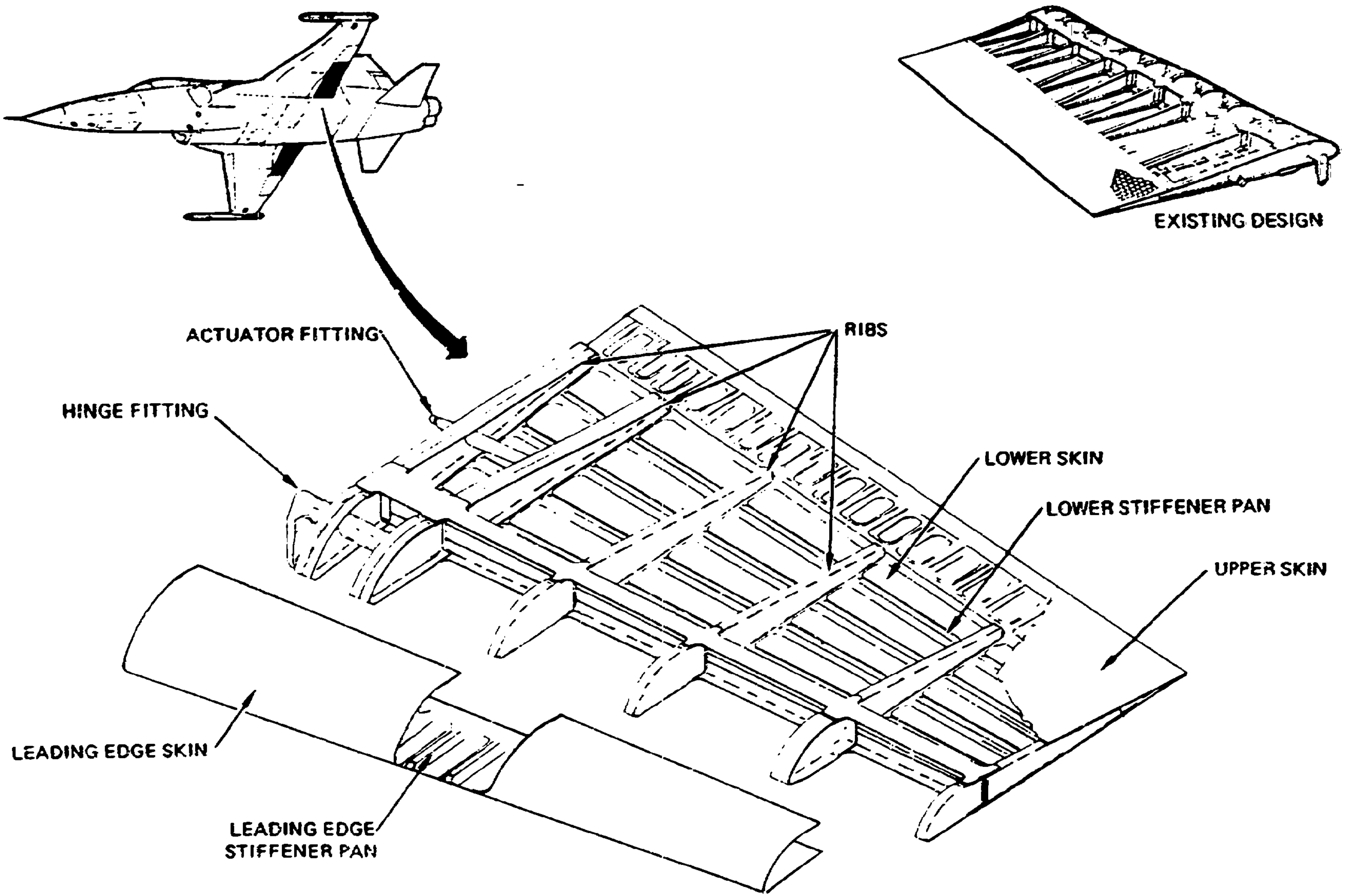

Figure 3. Baseline and SPF Trailing Edge Flap

The companion SPF design (Figure 3) investigates the trade-off of skin stiffening versus rib count and spacing. Every other rib was eliminated while spanwise beads were added as alternative skin stiffeners. At the trailing edge the stiffener pattern turned into a waffle pattern and replacing the separate honeycomb bonded assembly of the original design. The spanwise skin stiffening also eliminated the need for a forward spar. All the remaining ribs could be superplastically formed, eliminating the need for shear clips. The assembly of the deck could be accomplished by weldbonding and mechanical fastening.

CONCEPT 4 - Wing Leading Edge Extension

The original leading edge extension (LEX) is of conventional rib and spar construction, containing four machined ribs, three machined spars, a machined leading edge insert, ten sheet metal rib and spar segments, a wing attachment fitting and a one-piece skin. Two access panels are located on the under surface to provide access to the leading edge flap actuator mechanism. The leading edge extension is cantilevered off the wing leading edge spar except for a shear pin at the fuselage station 299 bulkhead.

The SPF design (Figure 4) replaced the internal ribs and spars with truss type corrugations running fore and aft. The upper and lower skins could be conventionally formed and bonded onto a SPF aluminum corrugated substructure. A one-piece machined leading edge and closing rib is mechanically attached.

2.1.2 Piece Count Reduction

SPF along with advanced joining techniques offers potential reductions in piece count and fastener count. The reduction in fastener count and piece count was obtained for all four candidate SPF parts. Table 1 shows a comparison of the piece count for the baseline components and their SPF design.

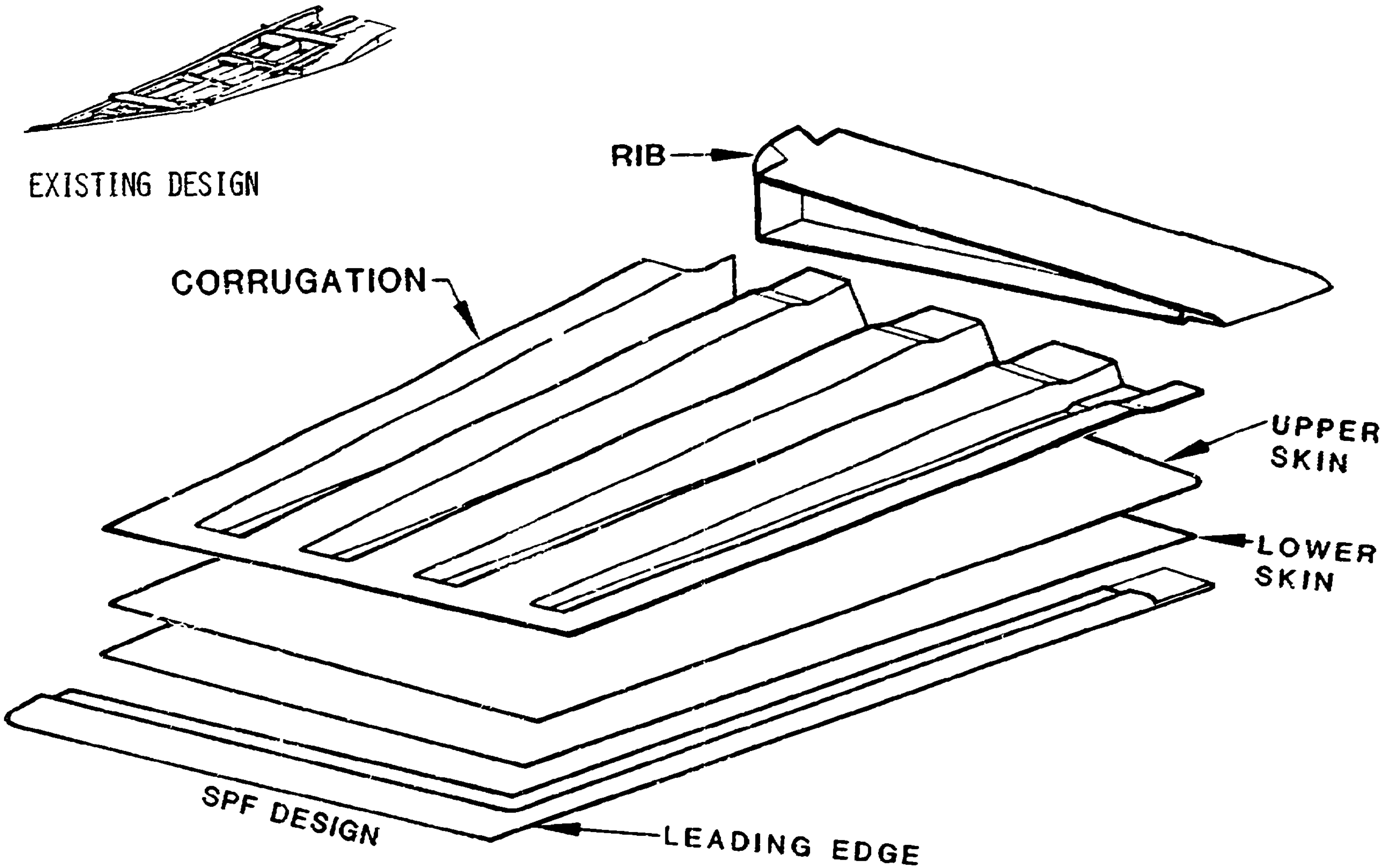

Figure 4. Baseline and SPf Leading Edge Extension

TABLE 1. PIECE COUNT REDUCTION

COMPONENT	BASELINE	SPF DESIGN	DELTA
AVIONICS DECK	63	10	-53
NOSE GEAR WHEEL DOOR	21	9	-12
TRAILING EDGE FLAP	98	42	-56
LEADING EDGE EXTENSION	2	5	+ 3

Significant reduction in piece count is seen for the avionics deck and trailing edge components. The number of parts for the leading edge increases by three. The original two-piece LEX was a one-piece substructure involving extensive machining. The SPF design shows significant cost and weight saving potential even though it increased the number of details.

The fastener count comparison for the baseline and SPF design is shown in Table 2. Significant reduction in fastener

TABLE 2. FASTENER COUNT REDUCTION

COMPONENT	BASELINE	SPF DESIGN	DELTA
AVIONICS DECK	1009	---	-1009
NOSE GEAR WHEEL DOOR	27	---	- 27
TRAILING EDGE FLAP	1049	474	- 575
LEADING EDGE EXTENSION	63	18	- 45

count is seen for the avionics deck and trailing edge flap due to the significant reduction in piece count and the use of weldbonding for the final assembly. The reduction in fastener count resulted in a significant savings in assembly costs.

2.1.3 Manufacturing Hours Estimates

Manufacturing hours estimates were obtained for all four candidate components discussed earlier. The manufacturing hours estimates were generated on a twelve shipset/lot basis. The hours given were cumulative to the third shipset (Table 3) or 300 shipsets (Table 4). The hours shown in Table 3 represent the methods and tools employed in this program and do not necessarily reflect normal production practice. A number of hand trim and drilling operations were assumed rather than a fully tooled production approach. No such deviations, however, were made with regard to the SPF forming dies. These tools were estimated as full production tooling. The tool design fabrication and planning hours estimates reflect program, not production, practices and are presented as a guide to program costs for full scale production.

For the purpose of this study, all baseline component manufacturing hours were estimated as if the F-5F were just going into production (T1) and not at the current production status (T1000+).

2.1.4 Component Ranking

The four components were rated, considering five main factors: recurring cost savings, weight savings potential, technology advancement, SPF risk and assembly risk. The component rating is shown in Table 5, based on a scale of 1 to 10 with 1 being the best. The recurring cost savings and program cost ranking reflect the manufacturing hours estimates previously given.

TABLE 3. THREE SHIPSET HOURS ESTIMATES

	AVIONICS DECK			NOSE GEAR DOOR			TRAILING EDGE			LEADING EDGE EXTENSION #1			LEADING EDGE EXTENSION #2		
	BASE	SPF		BASE	SPF		BASE	SPF		BASE	SPF		BASE	SPF	
TOOL DESIGN	----	1478	----	----	1040	----	----	2346	----	----	516	----	----	1408	----
TOOL FAB	----	5060	----	----	1532	----	----	13524	----	----	5178	----	----	5027	----
PLANNING	----	148	----	----	193	----	----	200	----	----	209	----	----	209	----
TOOL SUB TOTL	----	6686	----	----	2765	----	----	21070	----	----	5903	----	----	6644	----
FABRICATION	725	394	-331	101	124	+ 23	993	1335	+342	383	379	- 4	383	379	- 4
ASSEMBLY	124	98	- 26	208	114	- 94	1942	1073	-869	82	100	+ 18	82	117	+ 35
FAB SUB TOTAL	849	492	-357	309	238	- 71	2935	2408	-527	465	479	+ 14	465	496	+ 31
TOTAL		7178			3003			23478			6382			7140	

Tooling hours are included to show program cost impact. Hours shown are cumulative hours to T3.

TABLE 4. THREE-HUNDRED SHIPSET HOURS ESTIMATES

	AVIONICS DECK			NOSE GEAR DOOR			TRAILING EDGE			LEADING EDGE EXTENSION #1			LEADING EDGE EXTENSION #2		
	BASE	SPF		BASE	SPF		BASE	SPF		BASE	SPF		BASE	SPF	
FABRICATION	18848	12661	-6167	2667	4530	+1863	27142	39738	12596	20714	15259	-5455	20714	15259	-5455
ASSEMBLY	8045	5079	-2966	6927	4792	-2135	67401	58381	-9020	2810	4168	+1358	2810	5228	+2418
TOTAL	26893	17760	-9133	9594	9322	- 272	94543	98119	+3576	23524	19427	-4097	23524	20487	-3037

Tooling hours are not included. Baseline hours are estimated as a new vehicle (T1 to T300) not current production status (T1000+ to T1300+). Hours shown are cumulative to T300.

TABLE 5. COMPONENT RATING CHART

RATING CRITERIA	AVIONICS DECK	NOSE GEAR WHEEL DOOR	TRAIL-ING EDGE FLAP	LEADING EDGE EXTEN-SION
RECURRING COST	1	9	10	5
WEIGHT	3	10	5	5
TECHNOLOGY	1	7	3	5
SPF RISK	10	5	3	2
ASSEMBLY RISK	7	4	5	2
TOTAL	22	35	26	19

COMPONENT RATING: SCALE 1 THROUGH 10, 1 = BEST

The weight savings potential is somewhat of a subjective evaluation as the lack of a complete stress analysis precluded a detailed weight analysis. However, the substitution of the sheet metal SPF design for heavy hogout parts reduces the component weight significantly; hence, affecting the ranking order of these components.

The SPF avionics deck, through large reductions in piece count and fastener count, had significantly less linear inches of lap joint and thus, showed promise for a modest weight savings. The trailing edge flap piece count reduction did not produce a clear weight savings, however, the stiffened pan design was lighter than the existing rib/honeycomb design. The nose gear wheel door SPF design replaced a bonded honeycomb structure with little weight savings realized.

The risk and technology assessments were all highly subjective and require some explanation. The avionics deck contains areas with over 300 percent elongation, and nests channels between closely held fuselage outer mold line and the deck reference planes. Because its design requires the most accuracy and greatest superplastic deformation, it therefore ranks highest in technology advancement and highest in risk.

The nose gear wheel door offers considerably less risk because of more modest forming requirements. It is similar in design to many honeycomb replacement schemes used in SPF titanium and advanced composites, therefore, rating lower on the technology advancement scale.

The LEX represents the least risk because of modest SPF elongations (150 percent maximum) and an uncomplicated assembly. However, the skins require the development of dies capable of accepting preforms, and thus provide significant technology advancement.

The trailing edge flap required the same preform approach coupled with more severe deformations, and thus showed greater technology advancement. However, simpler assembly procedures and a more accommodating design reduce the program risks.

2.1.5 Recommendations

The rating chart (Table 5) shows the LEX design as ranking highest followed by the avionics deck with the trailing edge flap and the nose gear door a distant third and fourth, respectively. The relatively poor showing of the trailing edge flap is the result of its size, which is significantly larger than any other component, plus the large amount of parts and fasteners; 42 and 474, respectively. The size and final piece count contributes greatly to the program tooling costs making it the most expensive component to fabricate. The reason for the poor showing at the 300th shipset is caused by the long forming times of the many SPF details. Comparing the program quantity estimates with the 300 shipset estimates, showing an original hours saving, turns into a loss at 300 shipsets because of inherently flatter learning curves of SPF forming (fixed run times) and bonding.

Taking into account all the foregoing factors and rankings, it was decided that the best component candidates for full scale development were the avionics compartment lower deck assembly and the wing LEX. The avionics deck was selected as being the most cost effective and offered the most technology advancement. The LEX was recommended for its weight savings potential and least risk.

2.2 COMPONENTS DESIGN AND ANALYSIS

The details of design and analysis of the two selected parts are given in Reference 3. A brief discussion is given in the following paragraphs.

2.2.1 Avionics Deck

The original deck assembly is of conventional frame, intercostal and longeron construction. The frames and intercostals are of two-piece construction. This is to assure proper fit between the deck and skin. Shear clips are required at each frame and intercostal intersection to take up assembly tolerances.

In contrast, the modified SPF design shown in Figure 5 utilizes a one-piece waffle pan to replace several frames and intercostals. The deck is one-piece with the outboard edges flanged to provide the mounting flange for the avionics compartment access door and the necessary cross sectional area to function as the longerons in the original design.

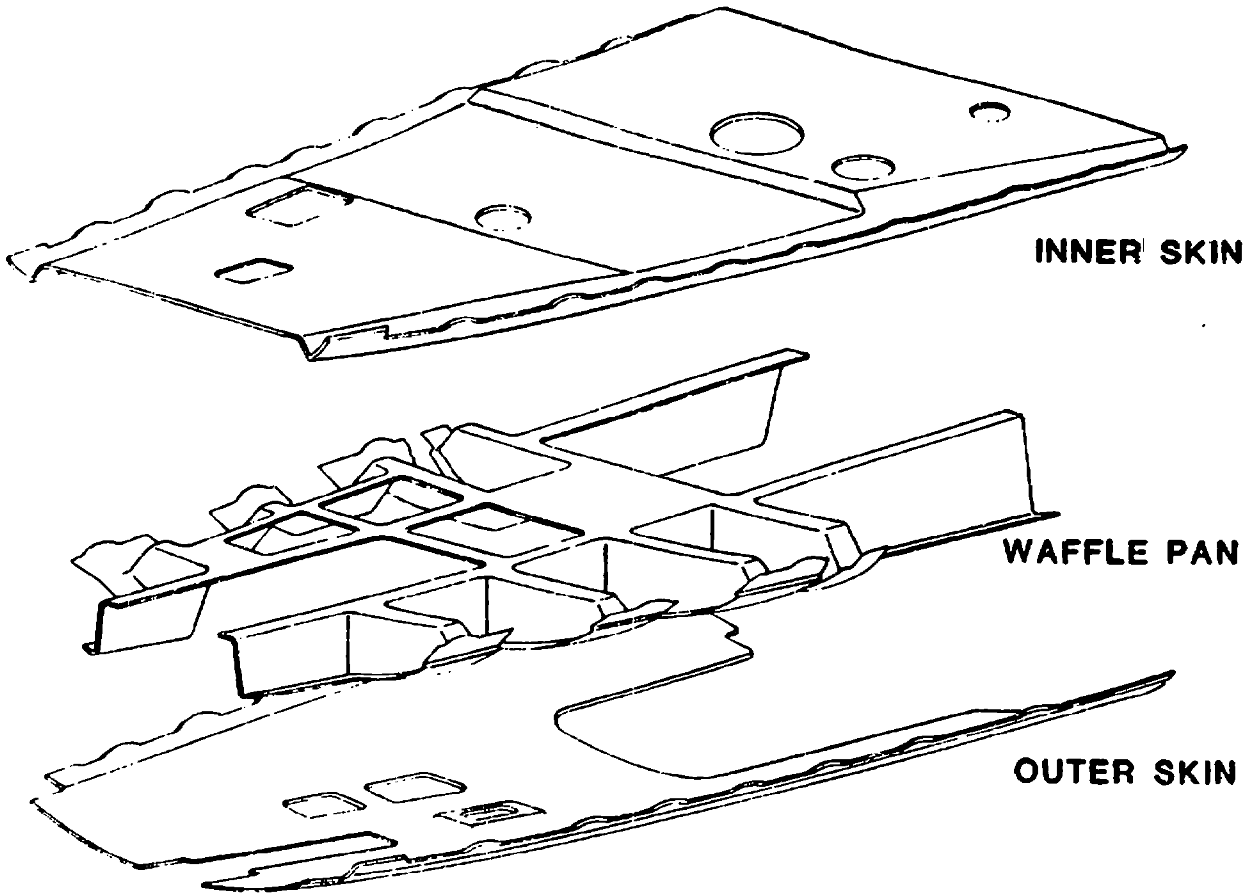

Figure 5. Modified SPF Avionics Deck

Full advantage is taken of the SPF process finer tolerances as all the substructural elements are devoid of separate moldline flanges and shear clips. The rivet bonding and adhesive bonding techniques used to assemble these components are only possible with SPF forming tolerances.

The configuration consists of three SPF parts (outer skin, inner skin and waffle pan), three machined parts, and four conventionally formed parts.

The avionics deck was analyzed using a NASTRAN finite element model. This model was created for the SPF avionics deck structure; the rest of the F-5F nose, between the bulkhead at fuselage station (F.S.) 47.50 and the bulkhead at F.S. 87.50, was modeled using the actual baseline structure to provide accurate results from loading conditions applied. This finite element analysis was necessary, because the unconventional structure in the SPF pan did not lend itself readily to conventional analysis due to the discontinuous load path in the pans. A rigorous model was necessary because; (1) the thickness gradients due to the forming process and the discontinuous load paths were not easily evaluated by conventional analysis, and (2) to ensure successful redistribution of the loads as compared to the baseline.

A total of nine loading conditions were evaluated:

(1) two supersonic inflight conditions

(2) two subsonic maneuver conditions (yaw and roll)

(3) three taxing conditions

(4) two miscellaneous pressurization conditions

The most critical loading condition was the supersonic symmetrical pull up at Mach 1.30, including internal pressure and inertial loading performed at 7.33 g's at an intermediate weight. The rigorous model and the many loading conditions were used to represent the actual structure as accurately as possible.

The results obtained from the model included internal loading, deflections and stresses. The peak stresses ranged from 4500 to 12000 psi at the critical areas located 1/3 the distance from the cantilevered edge. The critical areas were checked for buckling and crippling of the pan. In all instances, we achieved high margins of safety. A thinning analysis was performed on the critical area of the pan. The results of this analysis showed the most critical web located at the same area could be thinned to 0.037 inch.

Overall, the model proved the validity of the design concept. We concluded from these results that the limiting factor of the design concept would be the forming parameters rather than the stress levels.

2.2.2 Leading Edge Extension (LEX)

The SPF design of LEX is shown in Figure 4. It consists of upper and lower skins with SPF corrugations. The one-piece leading edge with closing rib and attached rib are machined parts. The corrugations are rivet bonded to the skin and leading edge, and the rib riveted to the resulting bonded assembly.

The LEX was also analyzed using a NASTRAN finite element analysis. It was modeled using CQUAD4 and CTRIA3, except for a few solid elements to represent the leading edge arrowhead fitting and the attach rib. Material thicknesses were evaluated and included on the model. The upper and lower skin thicknesses were a constant 0.065 inch and the rib web and flange thicknesses were 0.080 inch throughout. Corrugation thicknesses were acquired through a computer SPF thinning analysis. This program calculated the thicknesses of a SPF structure at various locations given the sheet gage and properties and the dimensions of the corrugations.

The loading on the LEX consist primarily of flight pressure loads. This pressure loading is a trapezoidal distribution running spanwise along the upper skin. The loads ranged from 9.97 to 18.02 psi, inboard to outboard, respectively.

The stress results from the flight pressure load case were less than 16 ksi allowing the upper and lower skin to be thinned down from 0.065 to 0.050 inch.

The results of the revised NASTRAN run yielded the maximum major principal stress of 35,565 psi located on the forward, inboard upper skin of the LEX. This stress is a localized stress which occurs in the area of the lug, a location which takes a majority of the loading. The minimum major principal stress was -4760 psi, which was located on the lower skin of the LEX in the same area as the maximum stress. Overall, the stresses on the upper skin of the LEX are low (<10 ksi).

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SECTION 3

MATERIAL SELECTION AND EVALUATION

This task was designed to do the preliminary screening of existing aluminum alloys and to select candidate alloys with SPF potential for further evaluation. The alloy having the best combination of SPF potential and post-SPF mechanical properties was selected for detailed evaluation and fabrication of airframe structures. The details of material selection and evaluation are given in Reference 3. The key steps in the selection process and the post-SPF properties of the selected alloy are briefly discussed here.

Subsequent to material selection, a new SPF aluminum material 'MD254' was developed by the Reynolds Metals Company. This material had better superplastic properties than the originally selected material (7475) and was therefore used for parts fabrication.

3.1 MATERIAL SCREENING

A preliminary screening of aluminum alloys was done to select three materials which were to be further evaluated for their SPF potential. These alloys were to be procured in a fine grained condition or given a thermomechanical treatment to refine their grain size.

The candidate materials included both ingot and powder metallurgy aluminum alloys and offered a broad range of service properties including strength, damage tolerance and durability. The ingot alloys; 7475, 7075, 7050, 2024, Supral 100, Alcan 08050 and powder alloy, X7091 were considered. The three alloys selected for preliminary evaluation and a brief rationale for their selection are as follows.

(1) 7475 Alloy. It is a high strength aluminum alloy with a relatively clean microstructure (fewer iron and silicon bearing inclusions than 7075, i.e., fewer natural sites for cavitation during the SPF deformation). It has strength and stress corrosion cracking resistance comparable to 7075-T6, and fracture toughness and exfoliation resistance (in 7475-T61 condition) superior to 7075-T6. It could be mill-produced in fine grained condition, has demonstrated capabilities for large superplastic deformation, and can be procured from several sources in the U.S.

(2) 7050 Alloy. It offers high strength and various other service properties characteristic of the 7XXX alloys. In addition, it has a lower sensitivity to the rate of quenching than other alloys in the same family. This property was considered desirable as optimum strength could be developed in an as formed 7050 SPF component by a slower cool than water quench, e.g., by air cooling. As a result, problems associated with warpage due to thermal stresses induced during quenching would be significantly reduced. Also, the presence of zirconium in the 7050 alloy also affords it more efficiency in grain refinement during mill processing. This alloy could also be easily procured from several domestic sources.

(3) X7091 Alloy. This alloy was selected because of its high strength, high corrosion resistance, and

excellent toughness (without compromising strength). Its superior properties are due to an inherently clean, fine grained and uniform structure in this alloy. The combination of the desirable service properties, typical of the 7XXX alloys, and the fine microstructure inherent in the P/M alloys like X7091, results in a structural aluminum alloy with a high SPF potential. This alloy can also be obtained from several sources.

3.2 MATERIAL SELECTION

The material selection was primarily based on the superplastic response, process parameters, maximum useful elongation, and post-SPF properties. The results of the preliminary evaluations were analyzed and a final alloy was selected that best fit the design requirements of the candidate components. Mill stock of three selected alloys, plates of 7475 and 7050, and extruded bars of X7091, were thermomechanically processed, heat-treated and rolled, into sheets with nominal gauge thicknesses of 0.060, 0.090, and 0.125 inch using the most desirable of the treatments developed under a joint Northrop - Reynolds IR&D program. A microstructural analysis and cone tests were conducted on the thermomechanically treated material.

The following paragraphs discuss microstructure and superplasticity capability evaluations which led to the choice of 7475 as the most suitable of the three alloys for use in this program.

3.2.1 Microstructural Evaluation

A three-dimensional microstructure evaluation was carried out for all three alloys. The details of these evaluations are described in Reference 3.

The 7475 sheet material exhibited the finest grain structure of the three alloys examined. The average diameter was between 8.3 and 9.1 micrometers, measured transverse to the sheet rolling direction. The standard deviations for these measurements were also the lowest. The average diameters in the direction parallel to the sheet rolling direction ranged between 13.0 and 16.3 micrometers.

The grain structure of the 7050 material was slightly coarser than that of 7475. The average diameter at the center line was between 10.2 and 11.9 micrometers, measured transverse to the sheet rolling direction. The grain structure in the center of the sheet was similar to that on the surface.

The microstructure of the X7091 material varied widely depending upon where the measurements were made. The grain structure in the center of the sheet was generally finer than away from it. The grains near the sample surface were very coarse with some of the average diameters exceeding 50 micrometers. These large grains were observed in all of the X7091 sheets produced by the various processing treatments.

3.2.2 Cone Tests

The classical approach of uniaxial tension testing for material plasticity evaluation was not used in the present investigation. Instead, the evaluation was done by biaxial tension forming of a cone shaped specimen. The main reason for this was to ensure that the test methods employed measured true material superplasticity in the aluminum alloys without being affected by other phenomena occurring which may influence their superplastic ductility. Aluminum alloys fail during the SPF process by a mechanism involving cavity nucleation at grain boundaries and cavity growth with increasing SPF strain rather than by the classical mechanism of necking from strain localization, as in Ti-6Al-4V and other titanium alloys. An elevated temperature uniaxial tension test performed on strips of these aluminum alloys, without suppression of cavitation, would result in a mixed-mode necking as well as cavitation failure and thus, would not measure true material superplasticity (necking by strain localization alone). The biaxial tension SPF cone test procedure suppresses cavitation during deformation and represented material behavior under conditions closer to those used in manufacturing operations.

Elevated temperature cone tests were conducted in temperature ranges of 850 to 970'F for 7475 and X7091 materials. Temperatures for 7050 sheets were slightly lower (850 to 935'F) due to lower solvus temperatures. Constant gas pressure in the range of 100 to 150 psi was used to impose several constant strain rates in superplastically forming a given cone geometry.

The results obtained from cone tests were plotted as log flow stress (σ) versus log true strain rate ($\dot{\epsilon}$), and a typical curve for 7475 material is shown in Figure 6. Similar curves were obtained for other thicknesses and materials. The strain rate sensitivity (m) versus log true strain rate curves corresponding to Figure 6 are shown in Figure 7. The log σ - log $\dot{\epsilon}$ curves are generally sigmoidal, a stretched S shape, with segments of lower values of slope (in regions of high and low strain rates) flanking a nearly linear segment of higher slope (in region of intermediate strain rate). The σ - $\dot{\epsilon}$ relationship in this intermediate region is described by the equation:

$$\sigma_{(\dot{\epsilon},T)} = k\dot{\epsilon}^{m(\dot{\epsilon})} \tag{1}$$

where, T is the test temperature and k a material constant. The m- log $\dot{\epsilon}$ curves, calculated from the slope of the log σ - log $\dot{\epsilon}$ curves ($m = \delta \log\sigma/\delta \log \dot{\epsilon}$), usually have a bell shape, with peak value lying in the intermediate strain rate range and having significantly lower values obtained in regions of high and low strain rates.

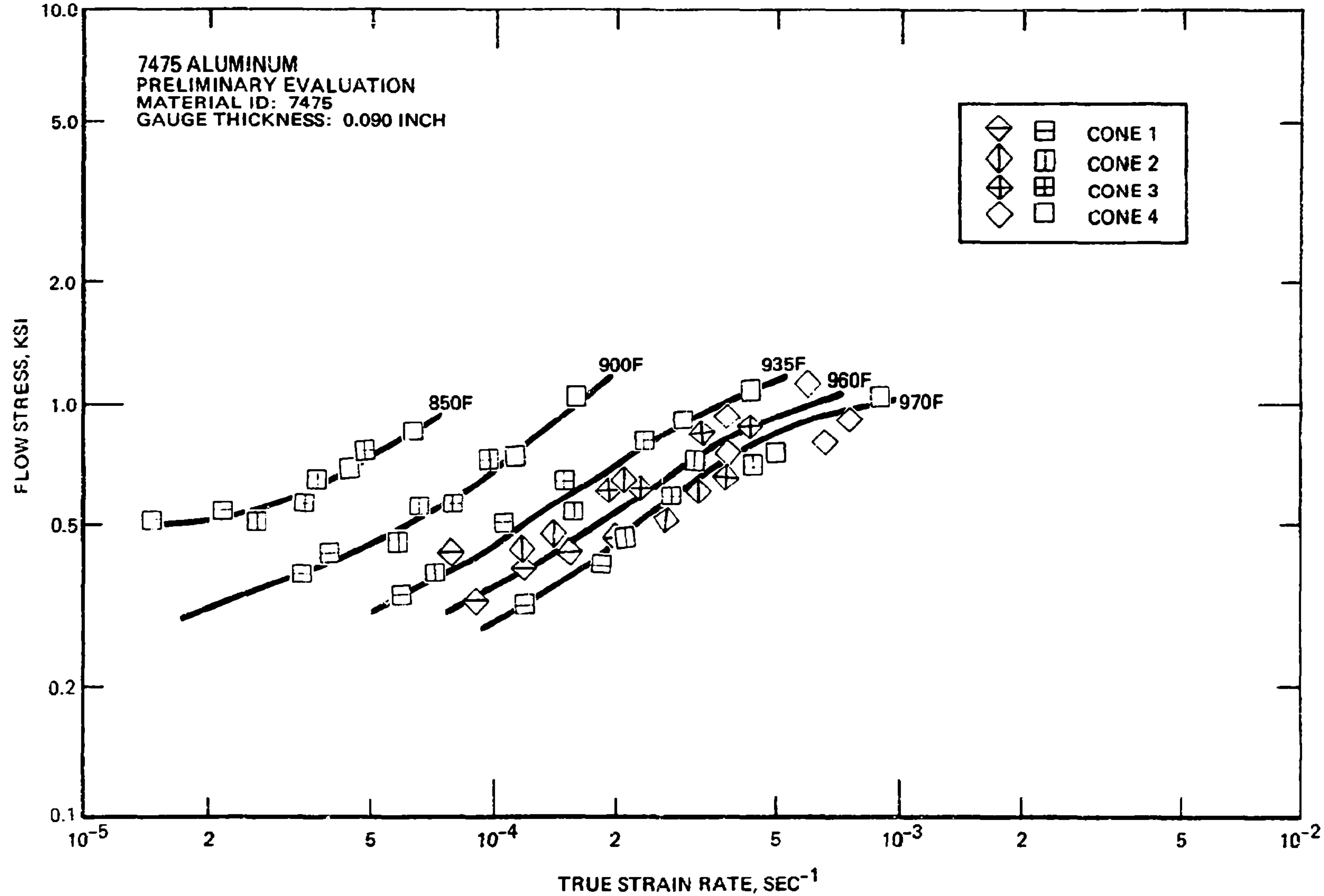

Figure 6. Plots of Log Flow Stress Versus Log True Strain Rate for 7475-II Material at Various Temperatures

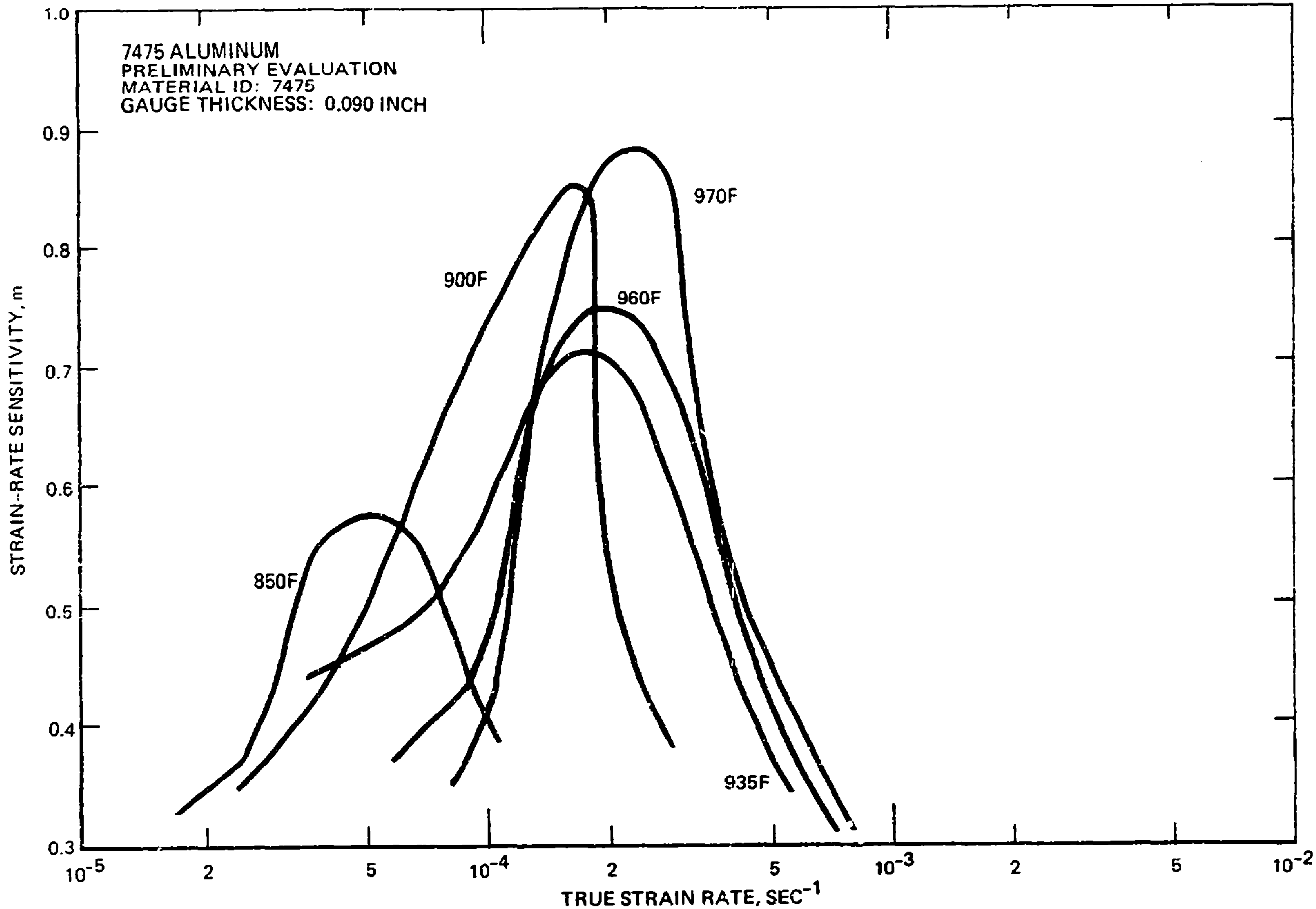

Figure 7. Plots of Strain-Rate Sensitivities (m) Versus Log True Strain Rate for 7475-II Material at Various Temperatures

A brief review of these results indicated that the 7475 alloy generally had the highest peak m values. The range of peak m values for the various sheet gauges evaluated over the temperatures of 900 to 970°F was 0.64 to 0.89. The corresponding peak m values were in the range of 0.59 to 0.89 (between the temperatures of 900 to 935°F) for the 7050 alloy and 0.3 to 0.5 (at 970°F) for the X7091 alloy. Higher peak m values are known to be related to superplastic elongation to fracture in a variety of materials (Reference 4). The higher the peak m value of an alloy, the higher is its projected superplastic elongation. The strain rates corresponding to the peak m were also in a higher strain rate range for 7475 than for the other alloys: 1.5×10^{-4} to 5×10^{-4} sec^{-1} for 7050 and 3×10^{-4} to 4×10^{-4} sec^{-1} for X7091. The differences in the strain rates are important, since higher strain rates would result in shorter fabrication time and, therefore, lower cost for a given component. Finally, the flow stresses corresponding to the peak m values were the lowest for 7475 of the three alloys evaluated: approximately 350 psi at 1.5×10^{-4} sec^{-1} and 1,000 psi at 10^{-3} sec^{-1} for 7475, compared to 400 to 500 psi at 7×10^{-5} sec^{-1} and 1,000 to 1,200 psi at 5×10^{-4} sec^{-1} for 7050, and 550 to 800 psi at 3×10^{-4} sec^{-1} and 650 to 900 psi at 4×10^{-4} sec^{-1} for X7091. Lower flow stresses are advantageous, since they translate into lower gas pressure requirements during forming and, due to the lower resultant stress concentrations, resulted in reduced cavitation.

3.3 MATERIAL EVALUATION

The 7475 alloy selected for the program was thoroughly evaluated for its SPF potential, post-SPF properties, microstructure, and secondary processability of the formed material. The properties of mill-produced and laboratory produced 7475 (0.090-inch and 0.125-inch thicknesses) were compared and comprehensive post-SPF mechanical property data, both static and fatigue, were obtained. Static properties were generated for longitudinal and transverse orientations, two initial sheet thicknesses, and three

SPF strains (50, 100 and 150 percent). Selected combinations of these variations were used for fatigue and environmental tests. We also investigated stress corrosion, exfoliation and fatigue crack growth in salt water.

Secondary processing factors examined included the ability of SPF material to accept paint, adhesives and anodic coatings. Spot and seam weld qualities and chemical milling were also evaluated.

The following observations were made from the above evaluation (Reference 3):

3.3.1 Cavitation Behavior of 7475 Alloy

Virtually no cavitation (<0.5 areal percent) was observed up to 60 percent SPF strain at three forming temperatures (850, 935 and 970°F). Beyond this strain, cavitation began to increase with increasing strain. Up to 100 percent strain was achieved with a cavitation level of 1 percent at 935°F temperature; this value of strain (with 1 percent cavitation) increased to 150 percent when the temperature was raised to 970°F. Beyond 100 percent strain at 935°F and 150 percent strain at 970°F, cavitation increased dramatically with increasing strain. Values of areal cavitation in excess of 12 percent were obtained with strains of 320 percent. As expected, the effect of higher temperatures was to suppress cavitation. The effect of temperature was to delay cavitation (due to a more efficient accommodation of cavities by the faster diffusion at the higher temperatures rather than to retard its rate. Thus, a higher temperature served to delay the onset of cavitation but did not significantly influence the rate of growth of cavities. Strain rate showed a similar effect on cavitation as temperature.

3.3.2 Mill-produced Versus Laboratory Material

SPF potential of 7475 mill-produced material (0.09- and 0.125-inch thicknesses) was comparable to that of laboratory produced material. The mechanical properties of mill-produced 7475 material in T6 condition were comparable to those of 7075-T6 aluminum sheet.

3.3.3 Tensile Tests

Tensile tests were conducted on SPF sheet coupons in accordance with ASTM E-8. Results obtained from post-SPF sheet thickness of 0.090 and 0.125 inch (with SPF thickness strains of 50, 100 and 150 percent) indicated that the ultimate and yield strengths as well as elongation were generally independent of the amount of prior SPF strain. The yield and ultimate strengths were above the MIL-Handbook 5 required values and the elongation was equal to or slightly below the MIL-Handbook 5 requirements. The rolling direction did not noticeably influence the post-SPF tensile properties.

3.3.4 Compression Tests

These tests were conducted in accordance with ASTM E-9. The compression strength for up to 150 percent SPF strain were appreciably higher than the MIL-Handbook 5 requirement.

3.3.5 Bearing Tests

Bearing specimens were tested in accordance with ASTM E238 for initial thicknesses of 0.090 and 0.125 inch. For the 0.125-inch thick sheet after a SPF strain of 150 percent, strengths were comparable to MIL-Handbook 5 values. However, for the 0.090-inch thick sheet, both ultimate and yield strengths met the MIL-Handbook 5 requirement within the SPF strain range of 50 to 150 percent.

3.3.6 Shear-Punch Tests

We found that the shear-punch strength values for 0.125-inch thickness were higher than MIL-Handbook 5 requirements. However, the 0.090-inch thick material had higher values than MIL-Handbook 5 requirements at SPF strains of 50 and 100 percent and slightly lower values for 150 percent strain.

3.3.7 Stress-Corrosion Tests

The stress-corrosion test was conducted on the post-SPF 7475-T6 specimens in accordance with ASTM G44. A stress equivalent to 74 percent of the yield strength of the 7475-T6 was exerted on each specimen which was alternately immersed in a 3.5 percent salt water at room temperature. Only specimens having an initial sheet thickness of 0.125 inch and superplastically deformed to 50 and 150 percent strains were tested. The average failure time was about 60 days, regardless of the magnitude of SPF strain, as compared to the required minimum failure time of 30 days.

3.3.8 Exfoliation Corrosion Tests

Exfoliation resistance of specimens formed at the three SPF strains was found to be comparable to conventional 7475-T6 material.

3.3.9 Fatigue Crack Growth Tests in Air

Fatigue crack growth in longitudinal transverse (L-T) and T-L directions in specimens, formed at 50 and 150 percent SPF strain, were found to be comparable to conventional 7475-T6 sheets.

3.3.10 Anodizing Tests

The post-SPF material in the T6 temper was observed to be identical to 7075-T6 in its response to the anodizing treatment.

3.3.11 Painting Tests

Using the standard procedures, no difference was observed in the paint adhesion characteristics of the post-SPF 7475 material and the conventional 7075 sheet. The post-SPF material also successfully met the impact and wet tape strength requirements in accordance with the Northrop specifications NAI 1269/NAI 1278.

3.3.12 Chem Milling Tests

Chem milling tests were conducted using Northrop's production facilities. The following results were obtained with regard to the rate of chem milling and the subsequent fatigue tests.

3.3.12.1 Chem Milling Rate

Thickness measurements were taken after submerging samples in the milling solution for one minute; this process was repeated five times and a cumulative metal removal in five minutes was calculated. The average chem milling rate in the post-SPF 7475 (T6 temper) was approximately 0.006 in/min, which is higher than 0.002 to 0.004 in/min for the conventional 7075-T6 sheet.

3.3.12.2 Fatigue Tests

Smooth fatigue tests were conducted by applying maximum stresses in the range of 30 to 50 ksi at a stress ratio (R) of

0.1. We observed that the fatigue life of the post-SPF 7475 after chem milling was slightly lower than that of the conventional 7475-T61 sheets. We believe that this difference may be related to some surface effects in the post-SPF material, since most of the specimens failed in areas other than the narrowest, and no cavitation was observed near the fracture region in the specimens examined. In the specimens tested in the present studies, the prior rolling direction (L or T) or the total SPF strain (50 or 150 percent) appeared to make no difference in the fatigue performance of the material.

3.3.13 Adhesive Bonding Tests

The following tests were conducted to determine the adhesive bondability and the resultant bond strength of the post-SPF material.

3.3.14 Lap Shear Tests

Post-SPF 7475 sheets were anodized in phosphoric acid, sprayed with BR127 primer, and bonded with FM73 film adhesive per Northrop Specification MA108. The average lap shear strength of six tests was 5400 lbs compared to the minimum strength of 4200 lbs required by the Northrop specification NAI 1286.

3.3.15 Climbing Drum Peel Tests

Even the lowest value of strength obtained (108 lbs/in) is higher than that for conventional high strength aluminum alloy sheets. However, the samples with low SPF strains had a higher strength (144 and 153 lbs/in) than those with high SPF strains (108 lbs/in).

3.3.16 Resistance Seam Welding Tests

Consistently defect free, reproducible resistance seam welds were obtained in the post-SPF 7475 (T6 temper) sheet specimens using the normal welding parameters for 7075-T6 sheets of equivalent thickness. X-ray radiography indicated no internal defects in the weld zone. Peel tests resulted in material failing outside the fusion zone, indicating the high strength of the seam welds.

3.3.17 Weldbonding Tests

We determined that the welding parameters established for 7075-T6 sheets can be reliably used to weld the post-SPF 7475 (T6) sheets of comparable thickness. Uncured joint strength values of 600 to 850 lbs were obtained, depending upon the welding current used. These values are the same as those normally obtained for the conventional 7075-T6 sheets. Surface treatment was based on the Northrop process specification.

3.4 MATERIAL SUBSTITUTION TO MD254

Following Northrop's IR&D evaluation of various new high strength SPF aluminum alloy sheets, a recommendation was made to the Air Force Program Monitor to substitute the selected material, 7475, with Reynolds Metals Company's new production 7475 alloy material, MD254, a highly superplastic alloy. In Northrop's evaluation, this material had been superplastically deformed to over 1,000 percent strain without appreciable (<0.5 percent area) cavitation. Following Air Force approval of this substitution, full size production sheets of MD254 were procured in 0.090- and 0.160-inch gauges and further evaluation was carried out.

The as received grain structure of the 0.090-inch thick material had the average longitudinal and transverse grain sizes of 17.0 and 8.5 m, respectively. Thus, the grains had an aspect ratio of 2.0. The 0.160-inch thick material had the average longitudinal and transverse grain sizes of 17.5 and 8.4 m, respectively.

Room temperature tensile tests were conducted on the material in T6 temper. The 0.090 inch MD254-T6 sheet properties compared quite favorably with the 0.090 inch 7075-T6 properties. The 0.0160 inch MD254-T6 strength properties were somewhat lower. The ductility of MD254 sheets in both thicknesses was considerably higher than that of 0.090 inch 7075-T6. In biaxial-tension cone tests at 970°F, the 0.090 inch thick sheets developed high thickness strains prior to rupture. In each case the dual pressurization approach was utilized for suppression of cavitation during SPF with strains over 1,000 percent. A significant fraction of these strains were found to be almost without cavitation. In one test, 1430 percent strain was obtained prior to rupture (at a strain rate of 1.3×10^{-4} sec^{-1}), virtually all of the strain was without cavitation (<0.5 percent). These results are shown in Table 6.

The 0.160 inch thick sheets also developed similarly high strains prior to rupture and much of the total strain was without cavitation. In the test specimen examined for cavitation, the strain obtained at rupture was 1925 percent. At a section representing 770 percent strain, cavitation was 0.01 percent and at 1520 percent strain the cavitation was 0.6 percent. The strain corresponding to 0.2 percent cavitation (<0.5 percent onset of cavitation) was estimated to be approximately 1,000 percent. The influence of SPF strain on cavitation is also shown in Table 6.

TABLE 6. EFFECT OF SPF STRAIN ON CAVITATION IN MD254 ALLOY

ALLOY	SHEET THICK-NESS (IN)	FORM-ING TEMP (F)	LOCATION OF SPECIMEN*								APPROXIMATE SPF STRAIN AT ONSET (<0.5%) OF CAVI-TATION (%)
			AREA 1		AREA 2		AREA 3		AREA 4		
			SPF STRAIN (%)	AREAL CAVITA-TION(%)	SPF STRAIN (%)	AREAL CAVITA-TION(%)	SPF STRAIN (%)	AREAL CAVITA-TION(%)	SPF STRAIN (%)	AREAL CAVITA-TION(%)	
MD254	0.090	970	28	0	84	0	311	0	1430	0.02	1430
	0.160	970	12	0	770	0.1	1520	0.6	>1520	3.0	>1000

*Results were obtained from biaxial SPF cone tests. Area 1 is near the die entry, Area 2 is where the cavities are first observed, Area 3 is intermediate to Area 2 and a region near the final failure (Area 4).

Uniaxial tension tests were also conducted on MD254 sheets at the same temperature (970°F) as the biaxial cone tests. These tests were performed without the use of hydrostatic compression for cavity suppression. The 0.090 inch sheet was tested in a strain rate range of 7.4×10^{-5} to 1.3×10^{-2} sec^{-1}. The maximum ductility (uniform elongation of 900 percent was obtained at 7.4×10^{-5} sec^{-1}. Approximately 700 percent elongation was obtained at 1.3×10^{-4} sec^{-1} strain rate, compared to a thickness strain of 1430 percent in the cone test on this material at the same strain rate using cavity suppression methods. The 0.160 inch thick sheet was tested in the range of 2.2×10^{-4} to 1.3×10^{-2} sec^{-1} strain rates. The maximum elongation in this range was 700 percent and was obtained at a strain rate of 2.2×10^{-4} sec^{-1}, compared to a thickness strain of 1925 percent in the cone test on this material at the same strain rate using cavity suppression methods. Figure 8 shows the plot of percentage elongation at failure vs. strain rate.

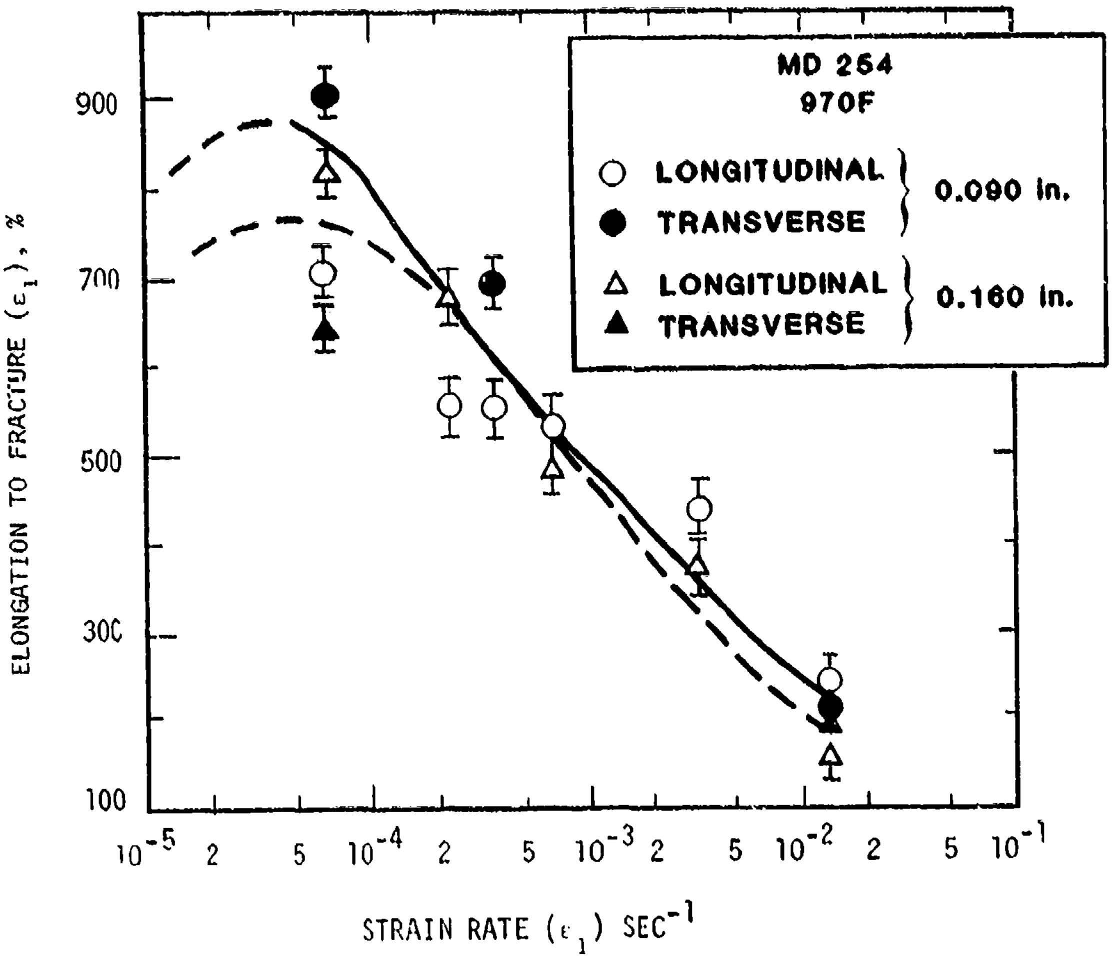

Figure 8. Variation of Percentage Elongation at Fracture With Strain Rate

Based on the above observations, it was decided to use the MD254 material rather than M7475 for fabrication of the SPF components.

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SECTION 4

PRODUCIBILITY FORMING TESTS

Producibility forming studies are perhaps the most important factor in the application of SPF technology for fabrication of complex parts using SPF technology, we must meet the minimum gage requirements set forth by designers. Edge and corner radii can be formed without cavitation and draft angles are such that the parts can be formed without affecting their quality. During the producibility studies, a number of subscale test parts are produced to verify the producibility and processing parameters of full scale components. The subscale parts are proportioned to simulate the critical forming areas of the full scale components. In making the subscale parts, the material is subjected to the same production and/or processing conditions as the respective full scale parts. The subscale parts are evaluated to determine the effects of SPF on microstructure, dimensional and thinning characteristics, cavitation, heat-treat response, fatigue and mechanical properties. The SPF part designs are modified based on the results of subscale part evaluations.

Producibility forming tests were conducted for the selected parts (LEX and avionics deck). The details of these tests are given in Reference 3. These tests are briefly discussed in the following paragraphs.

4.1 LEADING EDGE EXTENSION PRODUCIBILITY FORMING TESTS

The SPF substructure of LEX (Figure 4) has variable depth corrugations with compound curvature. A test subcomponent representing the deepest of the corrugations was selected for producibility forming tests (Reference 3). The geometry of the LEX is shown in Figure 9(a).

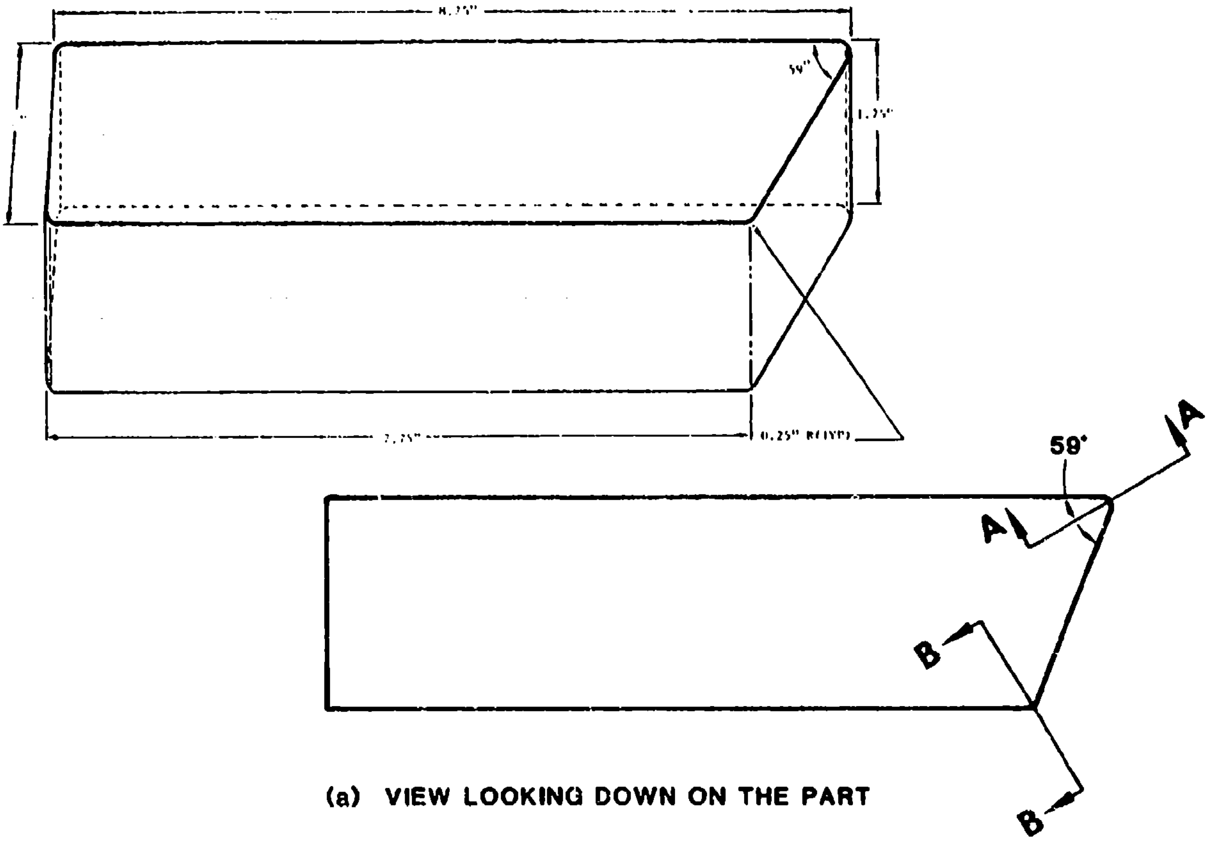
Reynolds superplastic aluminum alloy MD254 (0.09 inch thick) was used to make the LEX subcomponent. The forming was carried out at a strain rate of 2×10^{-4} sec^{-1} (the optimum rate from Figure 8). The measured forming rate was 1.4×10^{-4} sec^{-1}. Minimum thickness in the fully formed component occurred at the corner of acute angle and was found to be 0.015 inch. Figure 9(b) shows thickness measurements at various locations of two sections A-A and B-B. The maximum thickness strain on the formed part was 500 percent.

The formed part was sectioned through the acute angle for microstructural evaluations. Figure 10 shows the section along with the optical micrographs at various locations. The cavitation was measured using an image analyzer and is specified as an area fraction. At 350 percent thickness strain location, the area fraction of cavities was 0.8 percent.

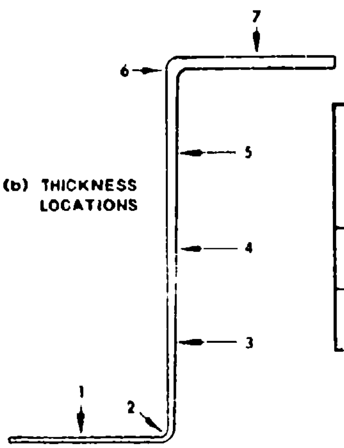
4.2 AVIONICS DECK PRODUCIBILITY FORMING TESTS

The outer and inner skins in the selected avionics deck represent a simple SPF forming and do not require producibility forming tests. The waffle pan, however, has a complex geometry and square deep pockets with a 15 degree draft angle on the walls. The most critical pocket was selected for producibility forming tests. The geometry of the selected pocket is shown in Figure 11. The tool for the subcomponent was machined from 4340 steel and was a self-contained unit with gas inlets and outlets.

Two subcomponents, one from 0.125-inch thick M7475 sheet and the other from 0.090-inch thick MD254, were fabricated. Superplastic forming was carried out at 970 ±10°F and at a strain rate of 3×10^{-4} sec^{-1}; with 400 psi back pressure. Reynolds



LEX SUBCOMPONENT



SECTION	PART THICKNESS IN INCHES AT LOCATIONS:						
	1	2	3	4	5	6	7
A-A	0.021	0.016	0.027	0.071	0.078	0.065	0.086
B-B	0.025	0.022	0.030	0.043	0.032	0.045	0.078

PART THICKNESS MEASUREMENT FOR LEX SUBCOMPONENT

Figure 9. LEX Subcomponent and Part Thickness Measurements

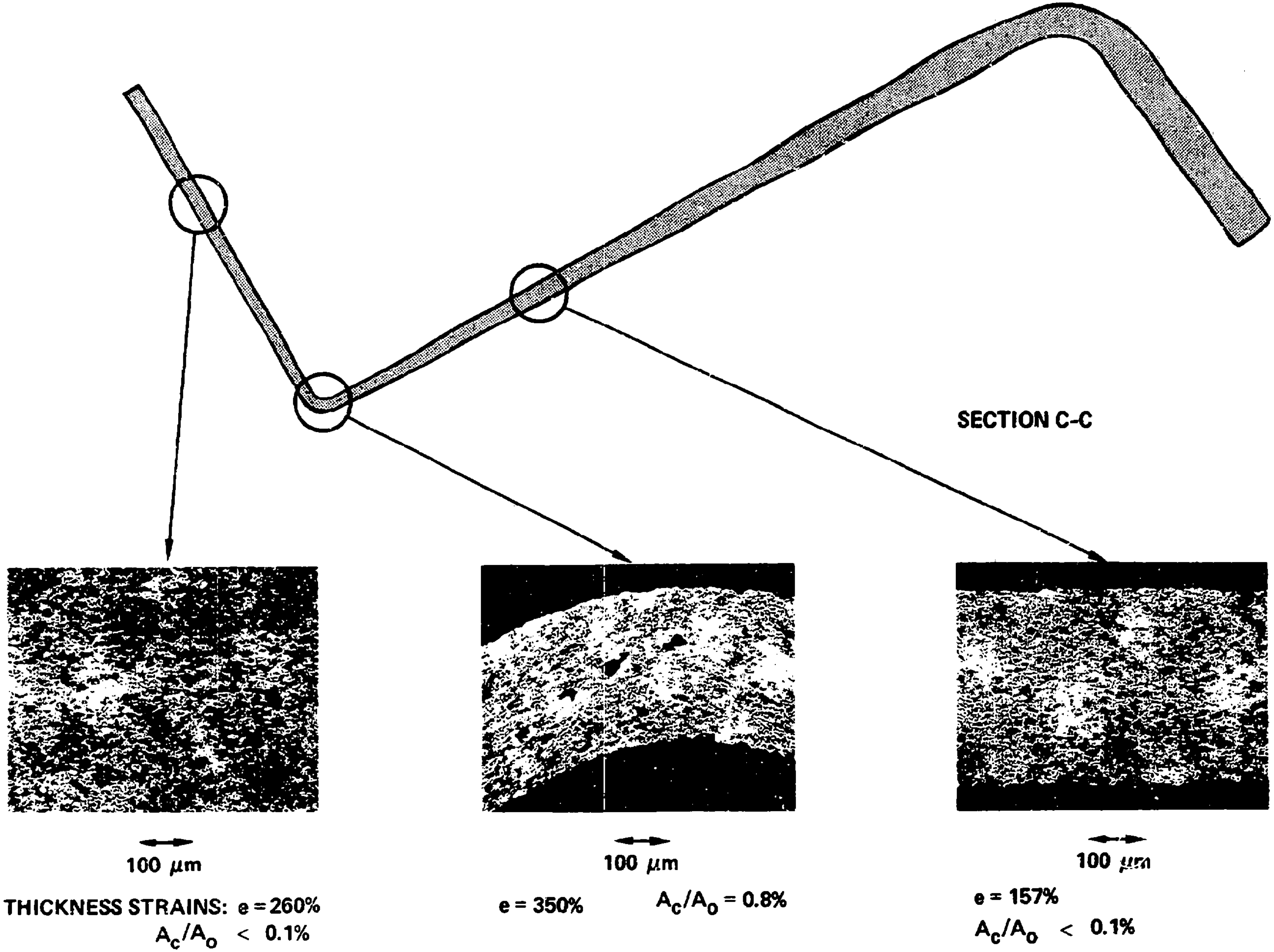


Figure 10. Cavitation Measurement from LEX Subcomponent

M7475 sheet ruptured during forming at a true thickness strain, e, of 1.43, whereas MD254 sheet ruptured at ϵ = 1.93.

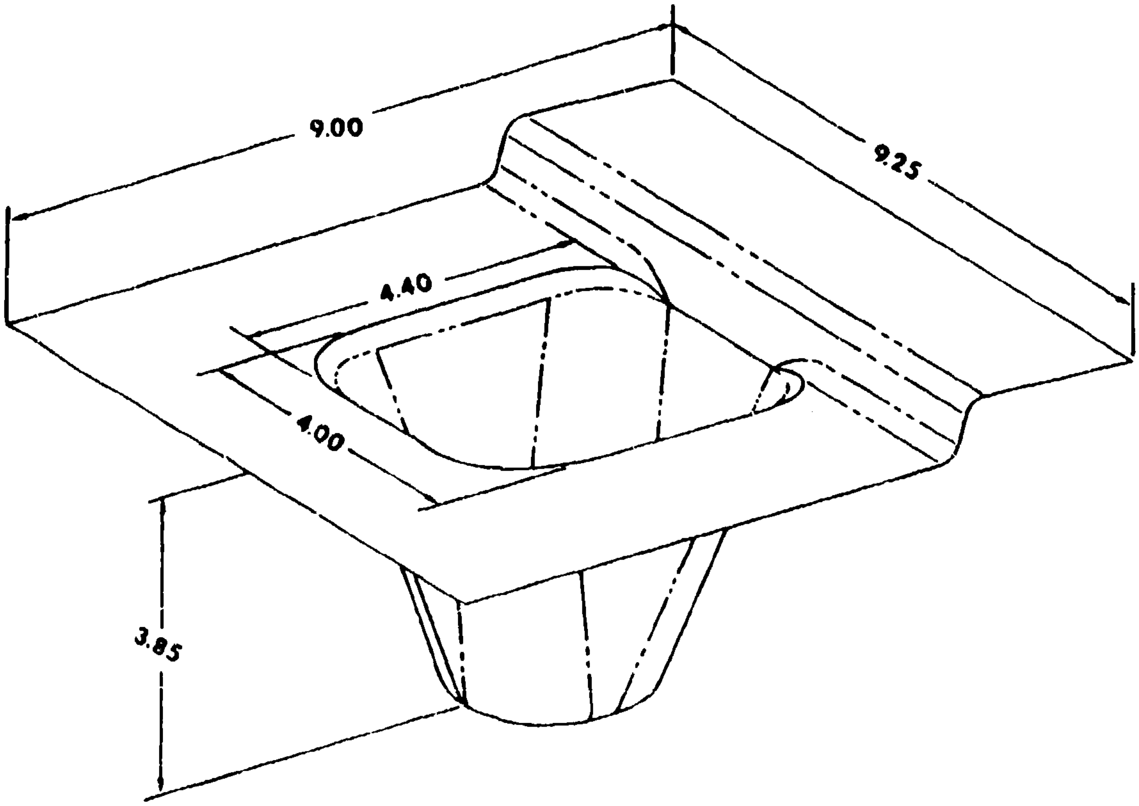
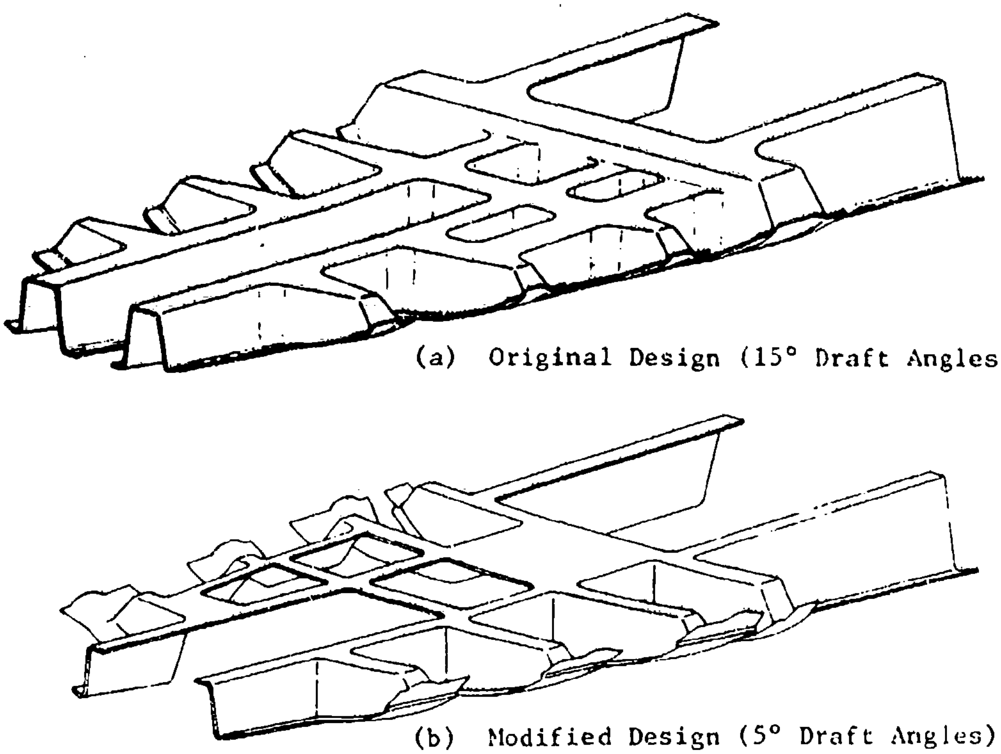


Figure 11. Original Design of Avionics Deck Producibility Subcomponents

We determined that the excessive thinning was occurring due to the high draft angle on the walls of an almost square pocket with an aspect ratio of about 1. Even if the part could be formed, it would be unacceptable due to excessive thickness gradients and not meeting the minimum thickness requirements. Hence, the waffle pan of the avionics deck assembly had to be redesigned. As a result, the waffle pan was redesigned with the aft center pocket eliminated and side pockets extended as shown in Figure 12. The draft angle was reduced from 15 degrees to 5 degrees. The configuration of the most severe pocket in the redesigned waffle pan was simulated in subcomponent forming.



(a) Original Design (15° Draft Angles)

(b) Modified Design (5° Draft Angles)

Figure 12. Avionics Deck Waffle Pan Modified Design

The subcomponent of the redesigned waffle pan was formed from 0.16-inch thick MD254 alloy. The fully formed part (Figure 13) met the acceptance criteria of both the minimum thickness and cavitation. Figure 14 shows the section of the subcomponent and optical micrographs at various locations. No cavitation is observed in the photomicrographs.

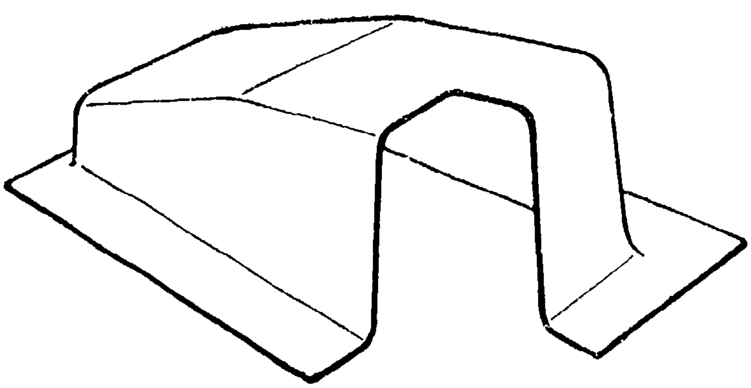
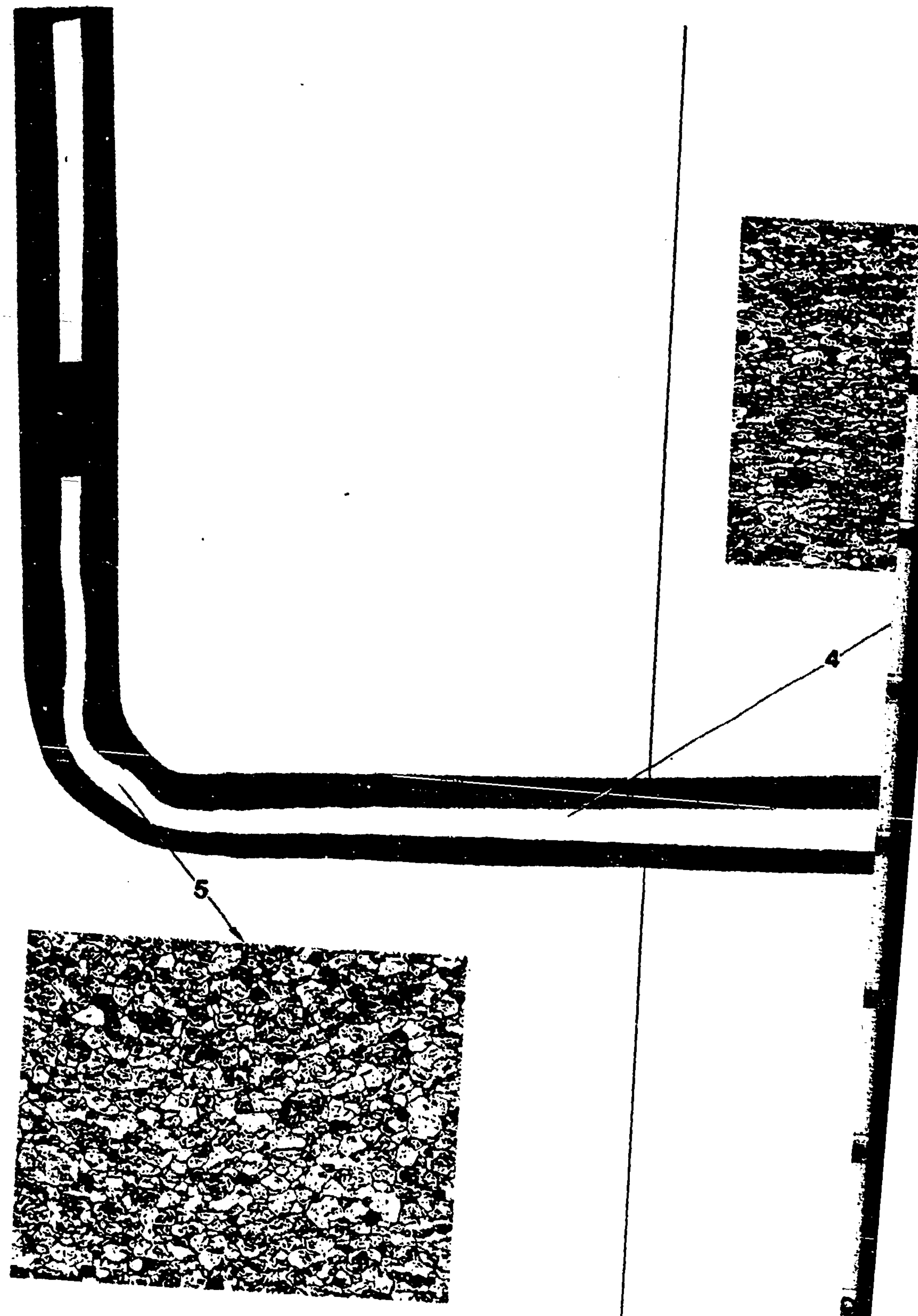


Figure 13. Avionics Deck Final Producibility Subcomponent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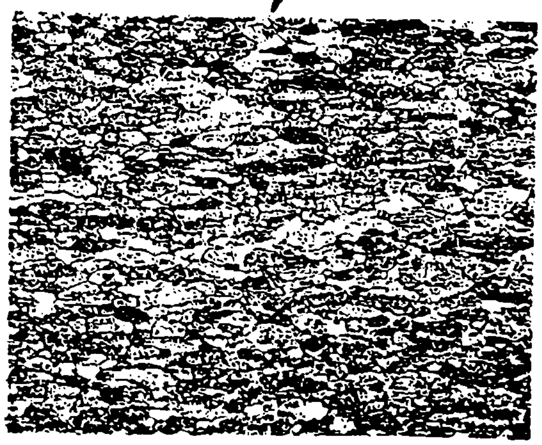
AVIONICS DECK - SUBCOMPONENT

3



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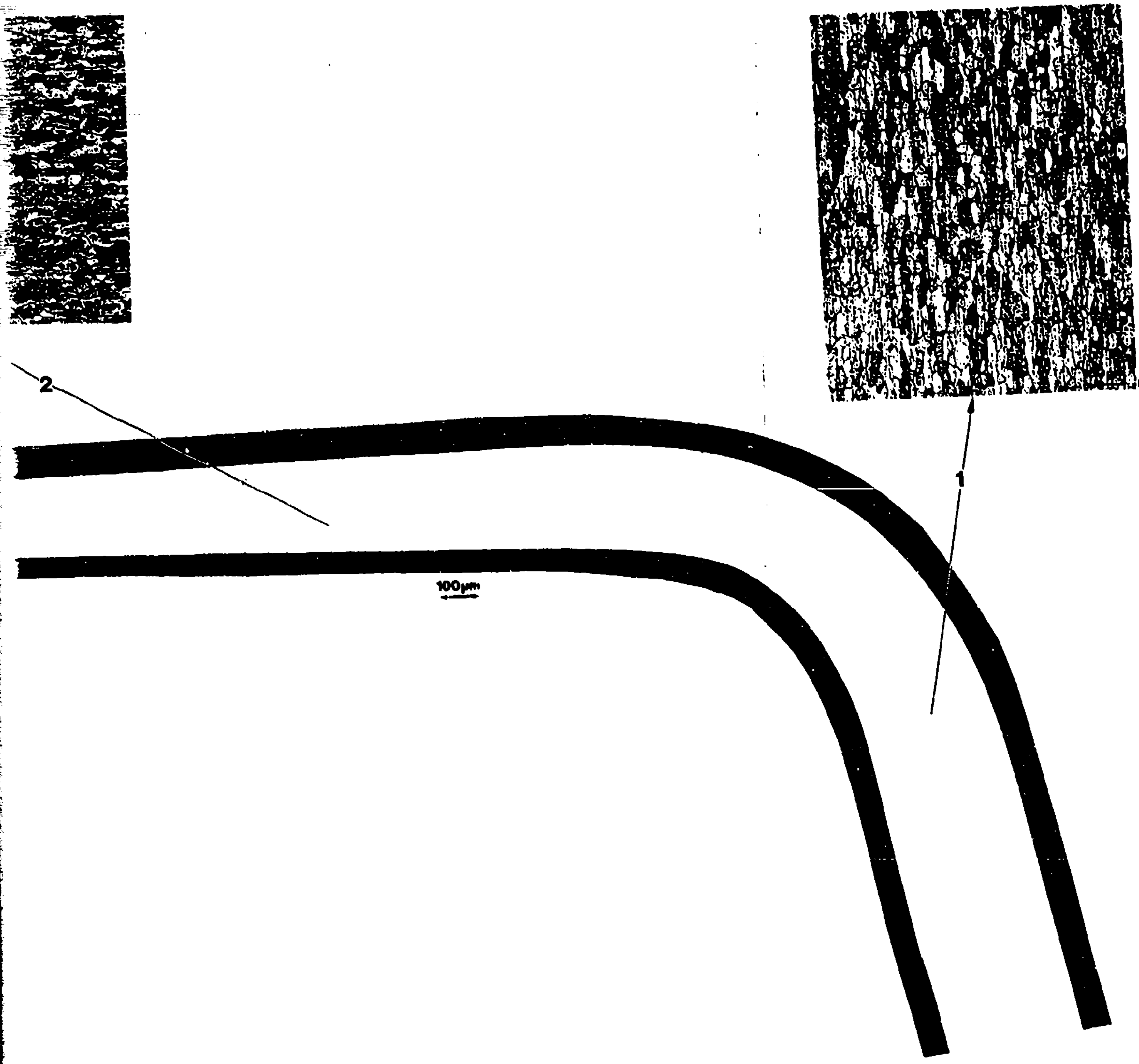


Figure 14. Avionics Deck Subcomponent Microstructure

3

4.3 COMPONENT MODIFICATIONS

Based on the results of producibility forming tests, a component redesign may be necessary in certain cases. This will be the case when new materials are introduced in SPF production. Modifications had to be made in the design of LEX and waffle pan, based on the forming tests, to ensure that thickness requirements were met and no cavitation occurred in critical forming areas.

Based on the small cavitation and thickness measurements observed in the LEX subcomponent, the corner radius was increased from 0.25 to 0.375 inch.

The subcomponent forming of the avionics deck clearly indicated that the original waffle pan design was not feasible for SPF production. As discussed earlier, necessary modifications were made in the design to ensure the forming feasibility and design requirements.

Once the forming feasibility tests have been successfully completed, the component design was finalized and tooling concepts developed for full scale production.

L E F T   I N T E N T I O N A L L Y   B L A N K

SECTION 5

PARTS FABRICATION, ASSEMBLY AND TESTING

The LEX and avionics deck full scale structural parts were superplastically formed using the tooling and fabrication concepts developed in the producibility forming task. Reynolds MD254 aluminum alloy was used for fabricating all SPF parts. One LEX component (corrugation) and three avionics deck components (outer skin, inner skin and waffle pan) were superplastically formed. The fabrication, assembly and testing of the parts is briefly described in the following paragraphs.

5.1 LEADING EDGE EXTENSION (LEX)

The LEX corrugation tool was profile machined from 4340 steel. It was a self-contained tool with seal edge and inlet-outlet gas tubes. Multi part gas inlet-outlet holes were used to prevent gas entrapment and for venting out the gas after forming.

The tool and the aluminum sheet were coated with boron nitride prior to forming. The superplastic forming was done at temperatures of 940 to 980°F. The tool was heated to the forming temperature and 0.090-inch thick MD254 aluminum sheet was hot loaded. The forming was done with a back pressure of 400 psi and a theoretical strain rate of 2×10^{-4} sec^{-1}. The average strain rate measured was 1.4×10^{-4} sec^{-1}.

The LEX corrugation was heat-treated to T6 temper subsequent to the forming. The heat-treatment was verified through electrical conductivity and hardness measurements. After heat-treatment, the SPF corrugations were chemically cleaned, anodized and primed. A typical LEX corrugation formed is shown in Figure 15. A total of three parts were formed without any failures.

Figure 16 shows a section of deepest channel end and optical micrographs from different locations on the section. There were a few areas containing isolated cavities, perhaps due to the variation in material grain structure. However, the area fraction of these cavities was less than 0.5 percent.

5.2 AVIONICS DECK

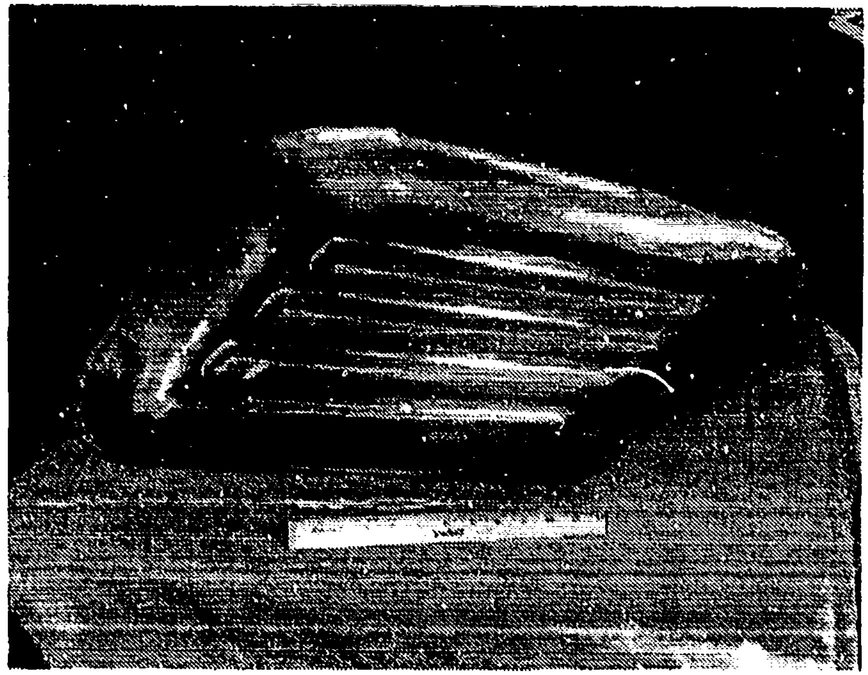
The avionics deck final assembly consisted of three SPF details, namely, (1) outer skin, (2) inner skin, and (3) waffle pan. The fabrication of these parts is discussed in the following paragraphs.

5.2.1 Fabrication of Outer and Inner Skins

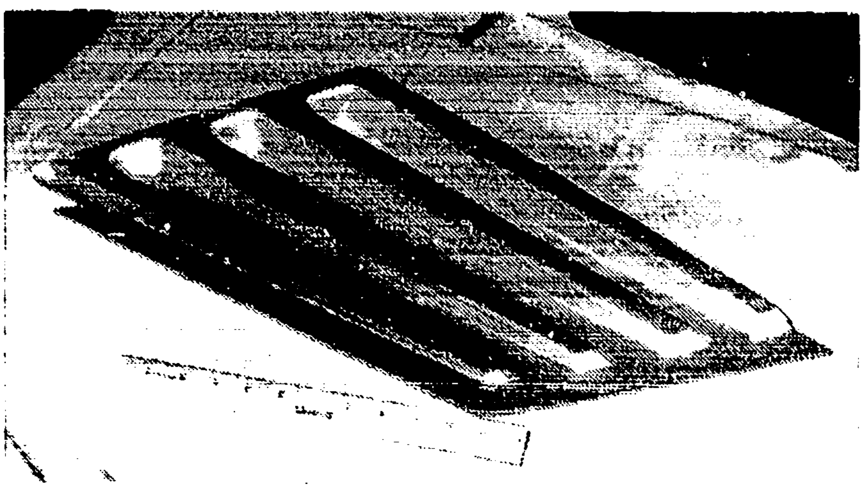
The outer and inner skins were superplastically formed from 0.040-inch thick MD254 aluminum sheet. The forming was done at a rate of 2 x 10^{-4} sec^{-1} in the temperature range of 943 to 977°F with 400 psi back pressure. Three outer and three inner skins were successfully formed with no scrap parts. The SPF outer skin and inner skin parts are shown in Figures 17 and 18, respectively.

5.2.2 Waffle Pan Fabrication

Waffle pans were superplastically formed from 0.160-inch thick MD254 aluminum sheet. A forming strain rate of 1 x 10^{-4} sec^{-1} was selected due to severe forming associated with the waffle pan. Six parts were superplastically formed without rupturing any part. A typical SPF waffle pan is shown in Figure 19. Thickness measurements were taken from five parts to determine the thinning variation. Typical thickness data are shown



(a) LEX Component Before Trimming



(b) LEX Component After Trimming

Figure 15. Superplastically Formed LEX Corrugations

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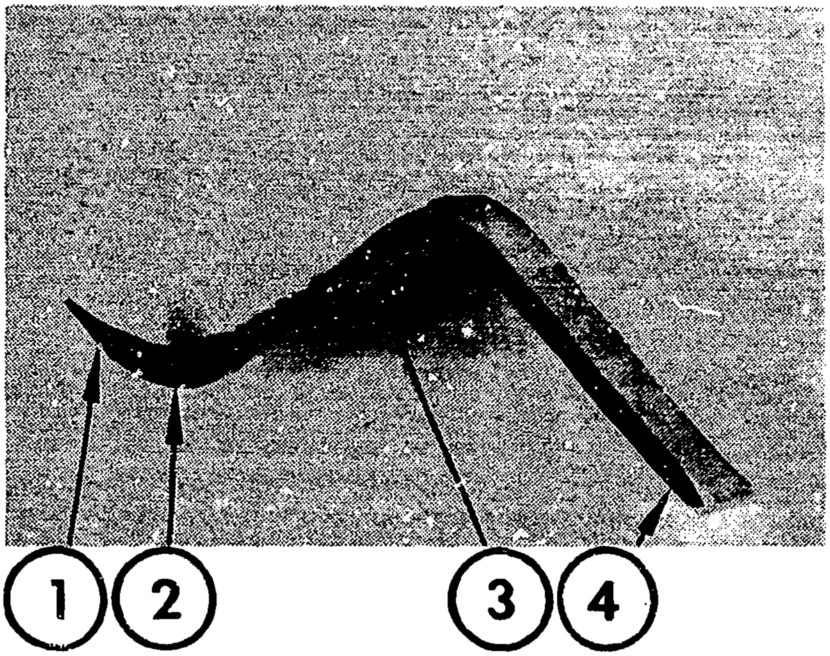

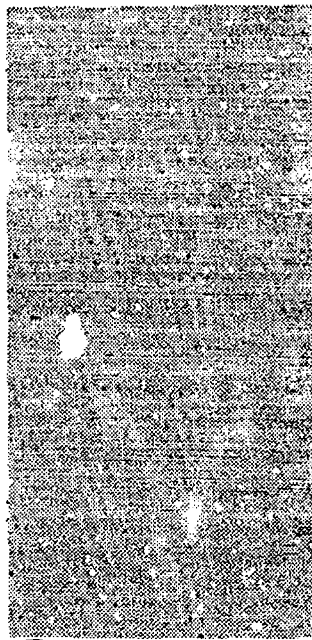

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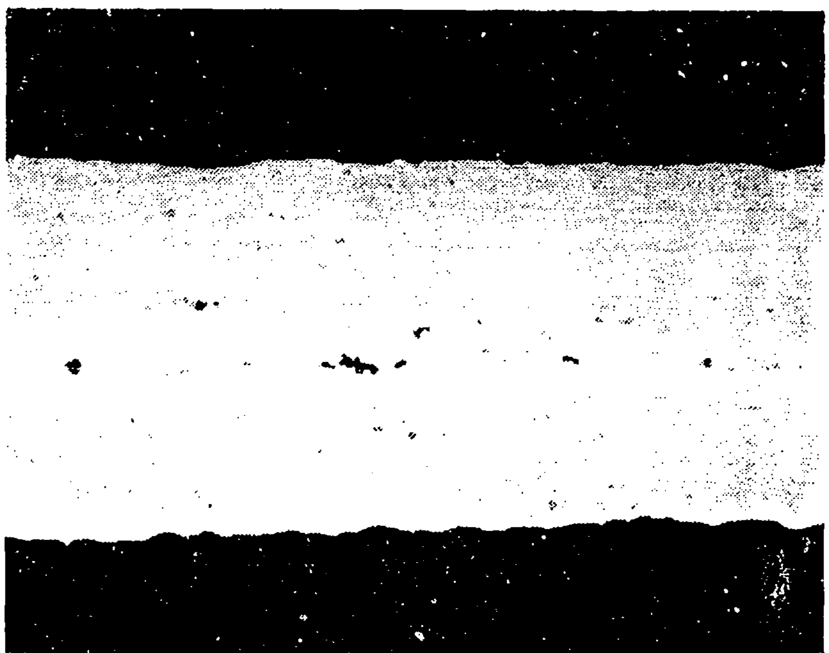

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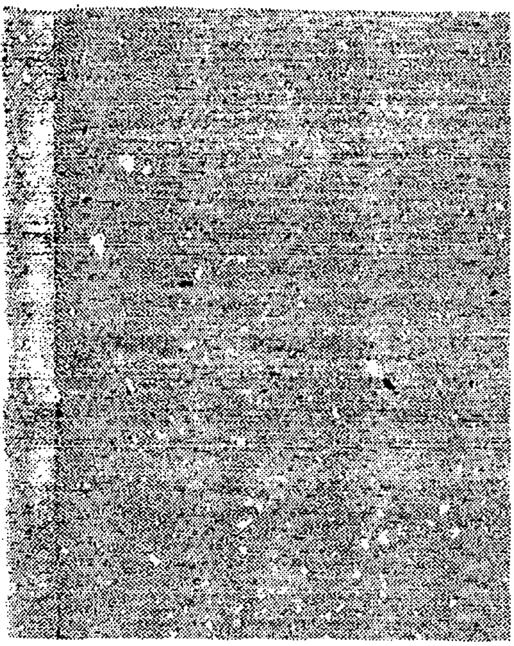

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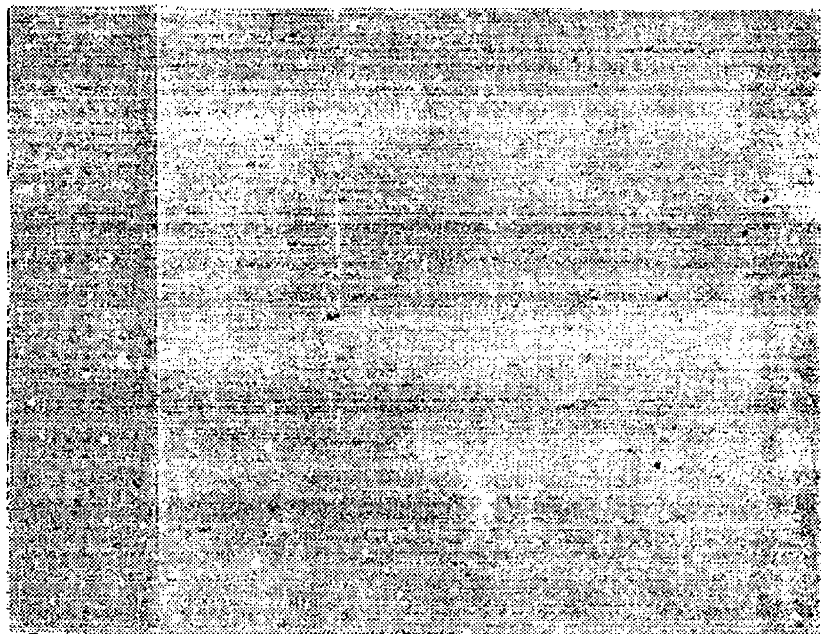

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2 100X

Figure 16. Optical Micrographs from Different Locations of the Section Through the Most Severe Forming Location

2

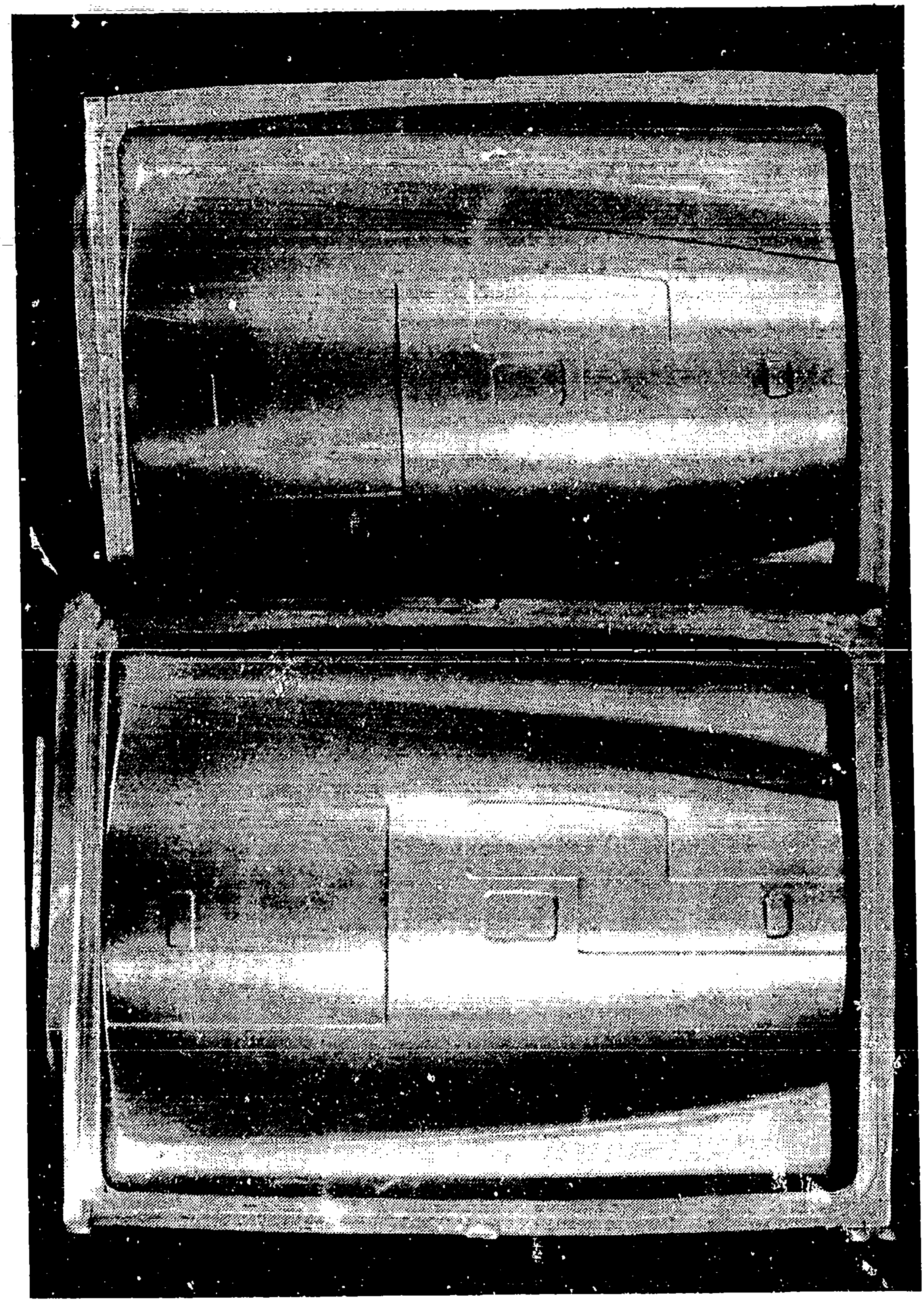

Figure 17. Superplastically Formed Outer Skin Parts

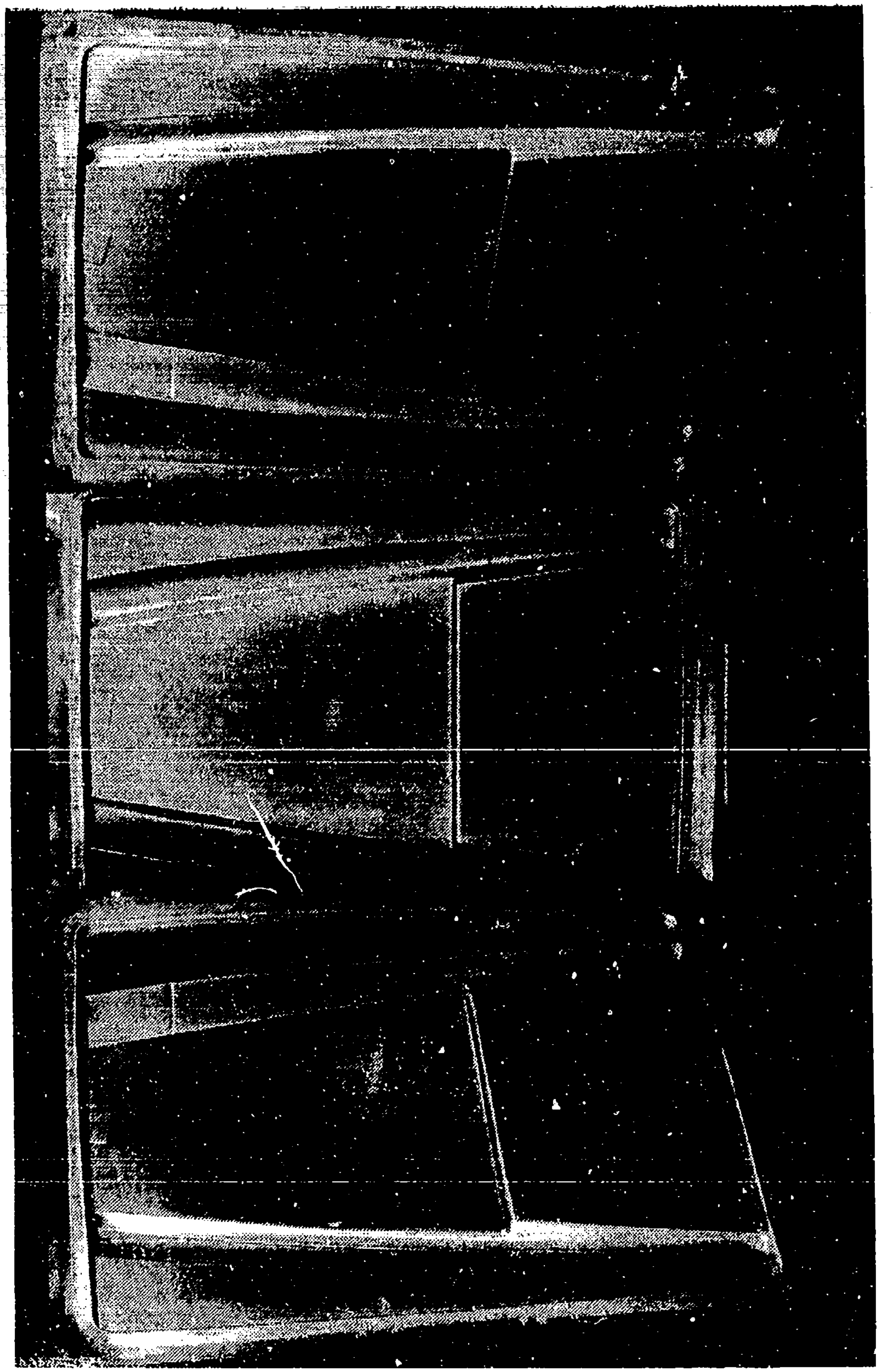

Figure 18. Superplastically Formed Inner Skin (Deck) Parts

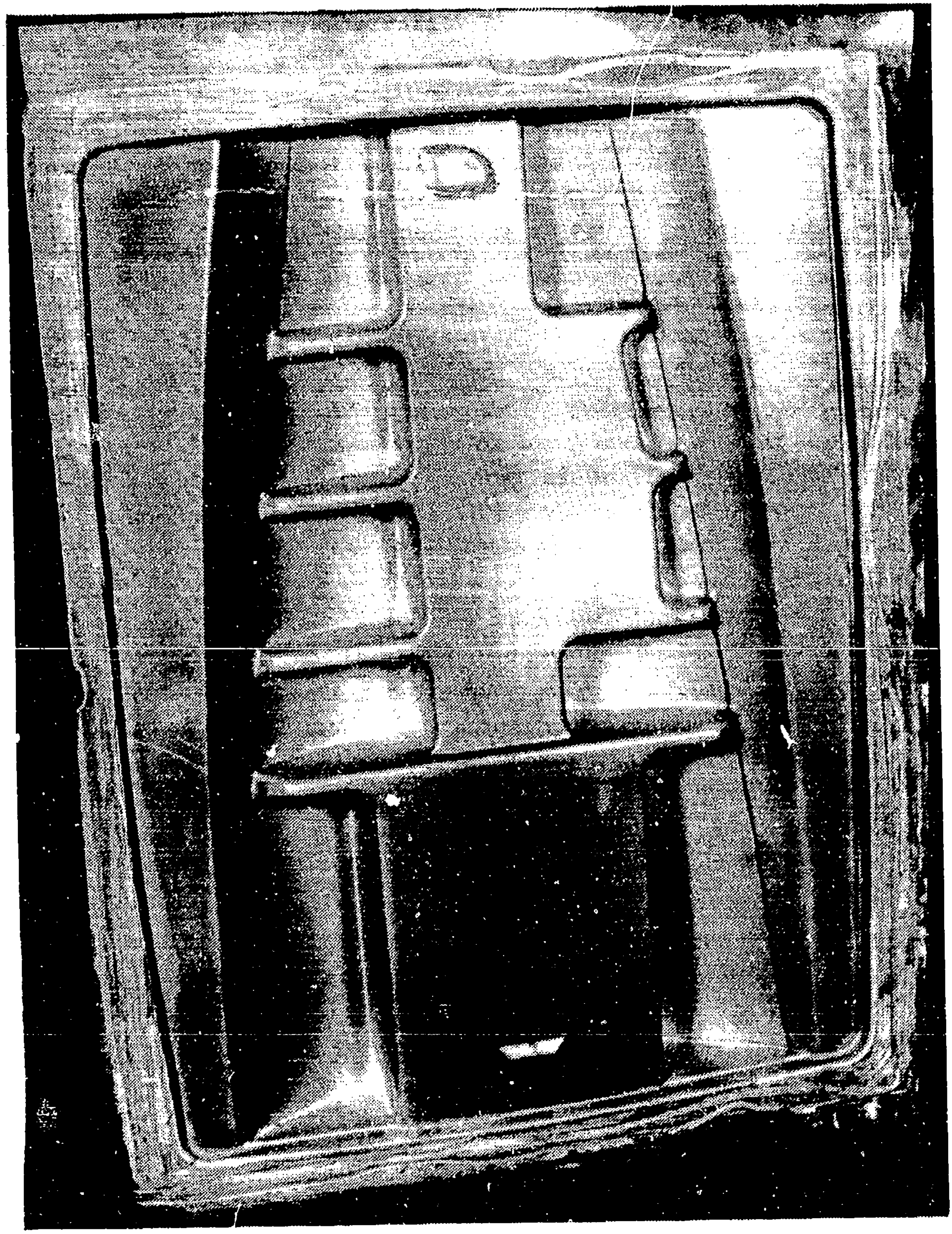

Figure 19. Avionics Deck Superplastically Formed Waffle Pan

in Figure 20. The thickness variations between five parts were found to be insignificant.

Optical microscopy was performed to determine cavitation at the areas of maximum elongation. Figure 21 shows a typical photomicrograph at a highly elongated location. No cavitation is indicated by the photomicrographs.

5.3 DECK ASSEMBLY

All the three SPF parts were heat-treated to T6 temper prior to deck assembly. The heat-treat was verified through electrical conductivity and hardness measurements. The three SPF parts were chem milled to remove excessive thickness and trimmed prior to the deck assembly. The waffle pan after chem milling and final trim is shown in Figure 22.

The final avionics deck assembly was completed using the rivet bonding concept. All three SPF parts and the substructural details were assembled utilizing the B.F. Goodrich A1444B paste adhesive. Application of rivets simulated the bonding pressure and simplified the curing process using an oven instead of an autoclave. The completed avionics deck assembly is shown in Figure 23.

5.4 AVIONICS DECK TESTING

The structural testing of the SPF avionics deck was conducted at the Air Force Wright Aeronautical Laboratories' testing facilities at Wright-Patterson Air Force Base. A detailed structural test plan was prepared by Northrop and reviewed by Air Force test personnel. The details of load conditions, static test and fatigue test are discussed in the following paragraphs.

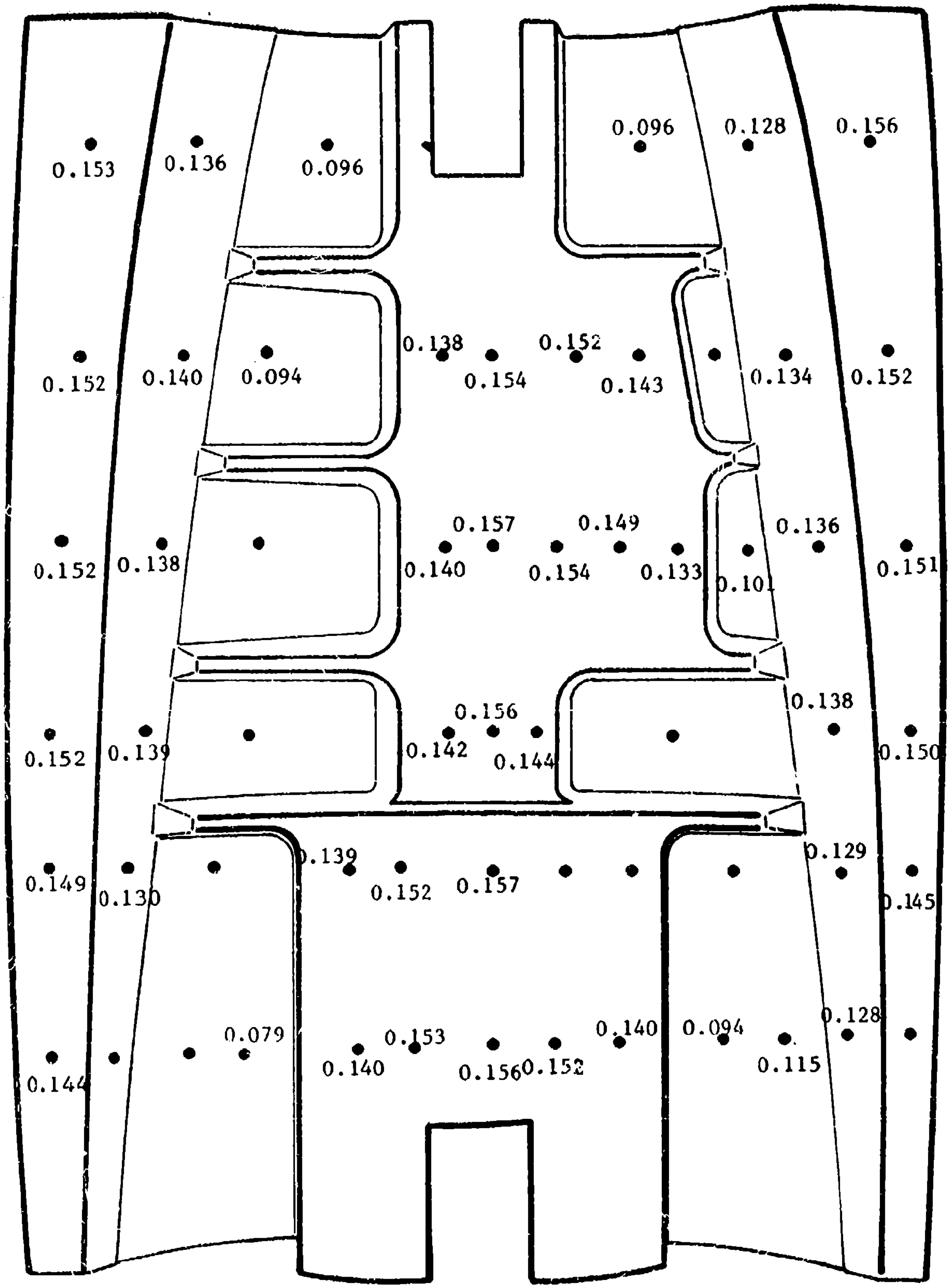

Figure 20. Thickness Profile of SPF Waffle Pan

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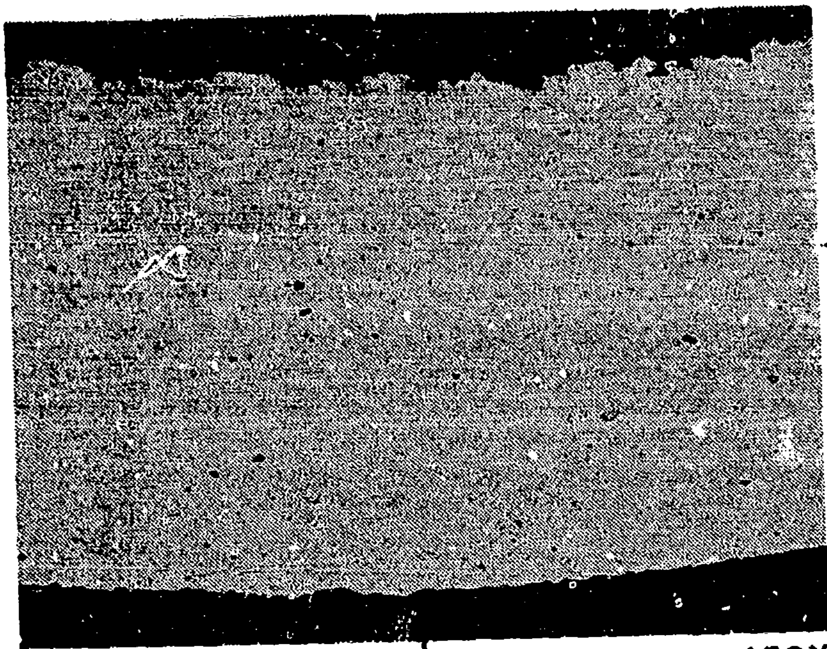

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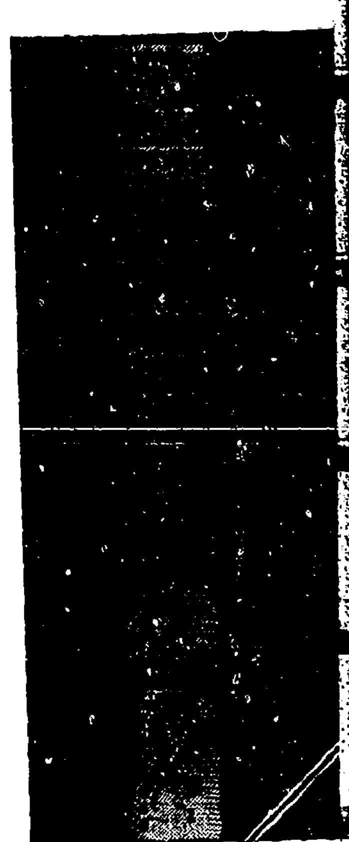

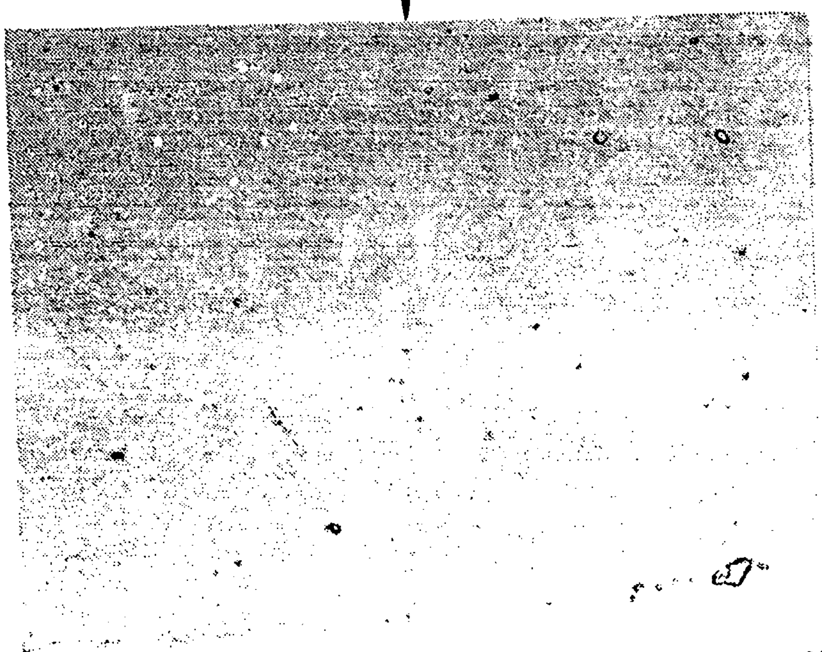

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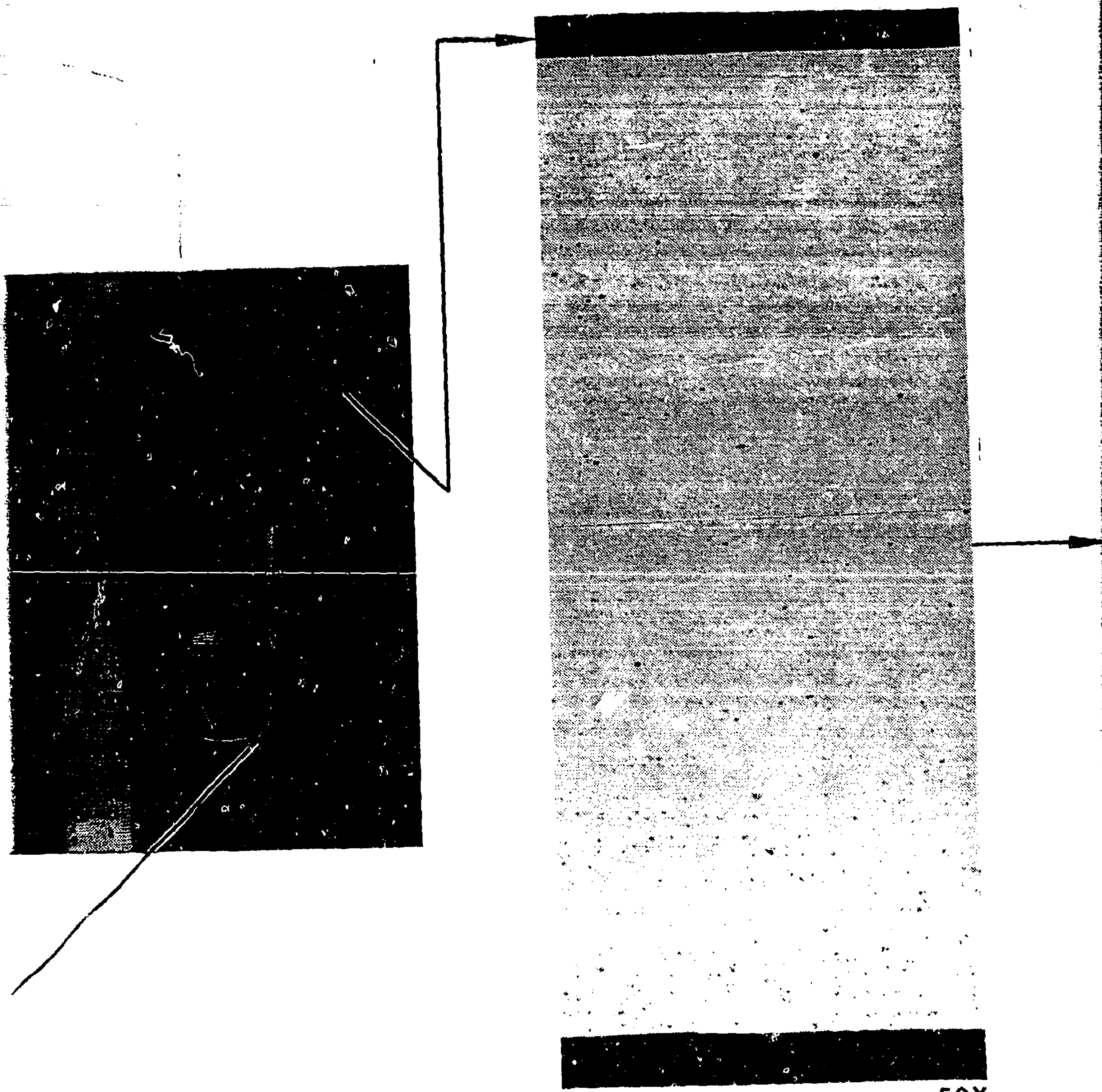

Figure 21. Optical
Waffle

2

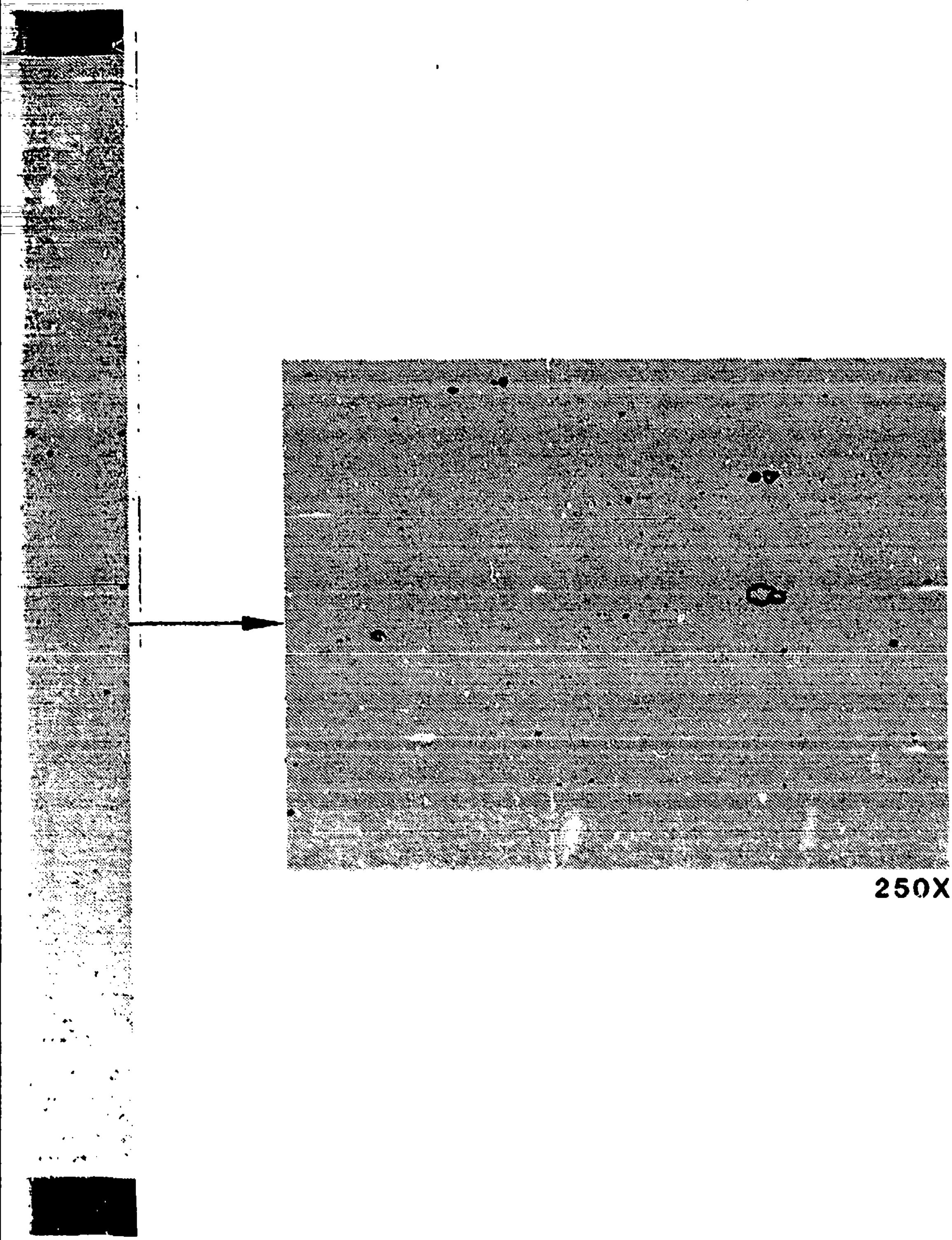

Figure 21. Optical Micrographs from the Deepest Corner of the Waffle Pan Showing No Cavitation

3

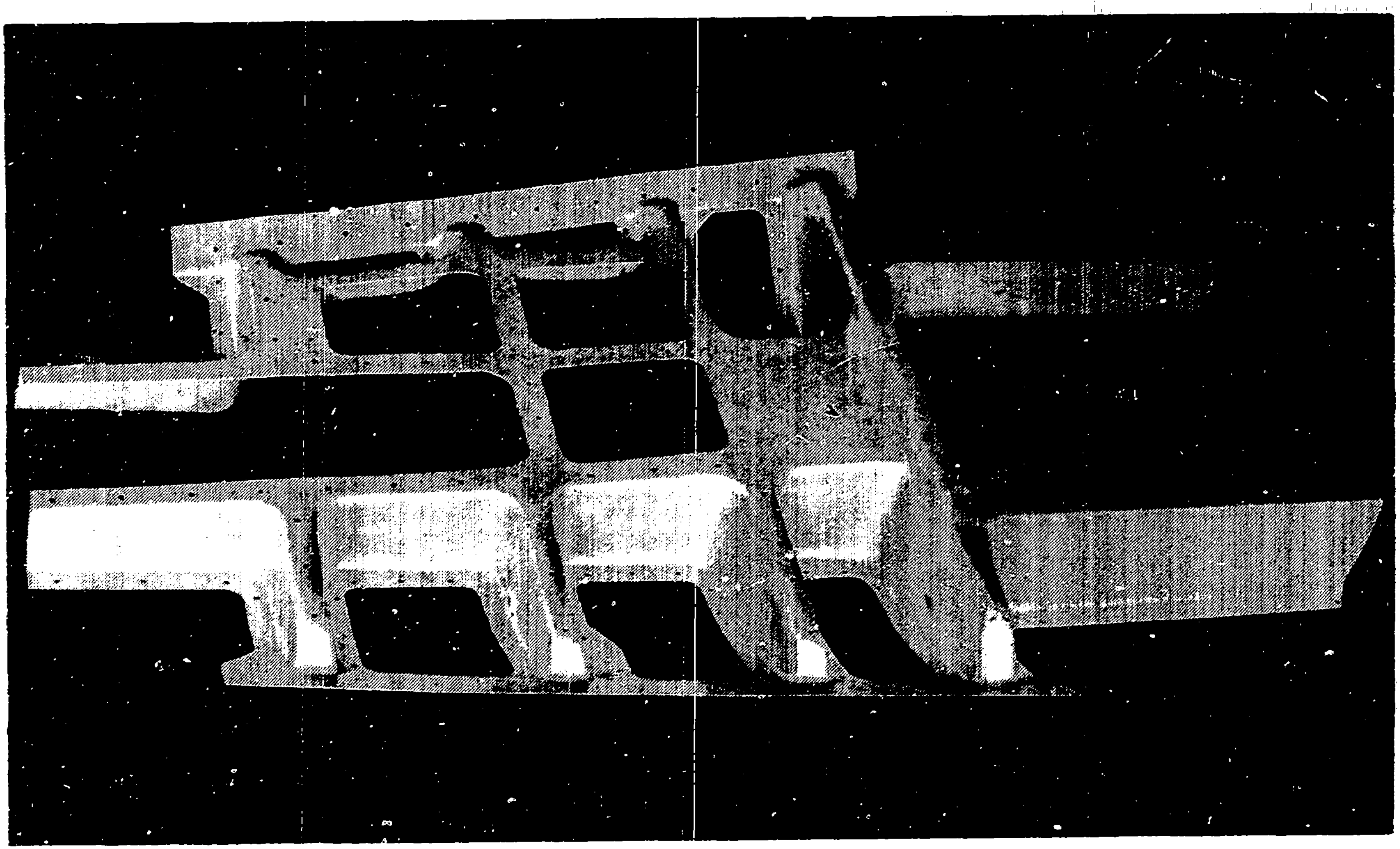

Figure 22. Avionics Deck Waffle Pan After Final Trimming

Figure 23. Avionics Deck After Assembly

5.4.1 Test Load Generation

The avionics deck is in the forward fuselage between stations F.S. 47.50 and 87.50 of the F-5 aircraft. The forward fuselage structure between these stations is subjected to gun blast pressure due to a gun barrel located on the left hand side between the upper skin and the deck. In addition to the gun blast pressure, the avionics deck is subjected to internal pressure loading (cockpit pressure), external pressure loads and the inertia loading of the structure and equipment. The deck is designed for the following loads.

(1) Maximum cockpit bursting pressure of 3.98 psi.

(2) External air pressure linearly varying from a 1.4 psi collapsing pressure at F.S. 47.50 to a 0.8 psi bursting pressure at F.S. 87.50 (bottom centerline pressure for a symmetrical pull up under supersonic mach numbers).

(3) Inertia loading due to equipment assembled onto the deck.

The avionics deck test loads were selected to satisfy the flight load conditions. These loads were represented by four reaction loads (P_1, P_2, P_3 and P_4) as shown in Figure 24. The function of each load is described below.

P_1: To satisfy the upper and lower skin axial loads between F.S. 47.50 and 62.50. This load, as shown in Figure 24, is applied slightly above the centerline of the deck in order to distribute the upper and lower skin axial loads in an appropriate manner.

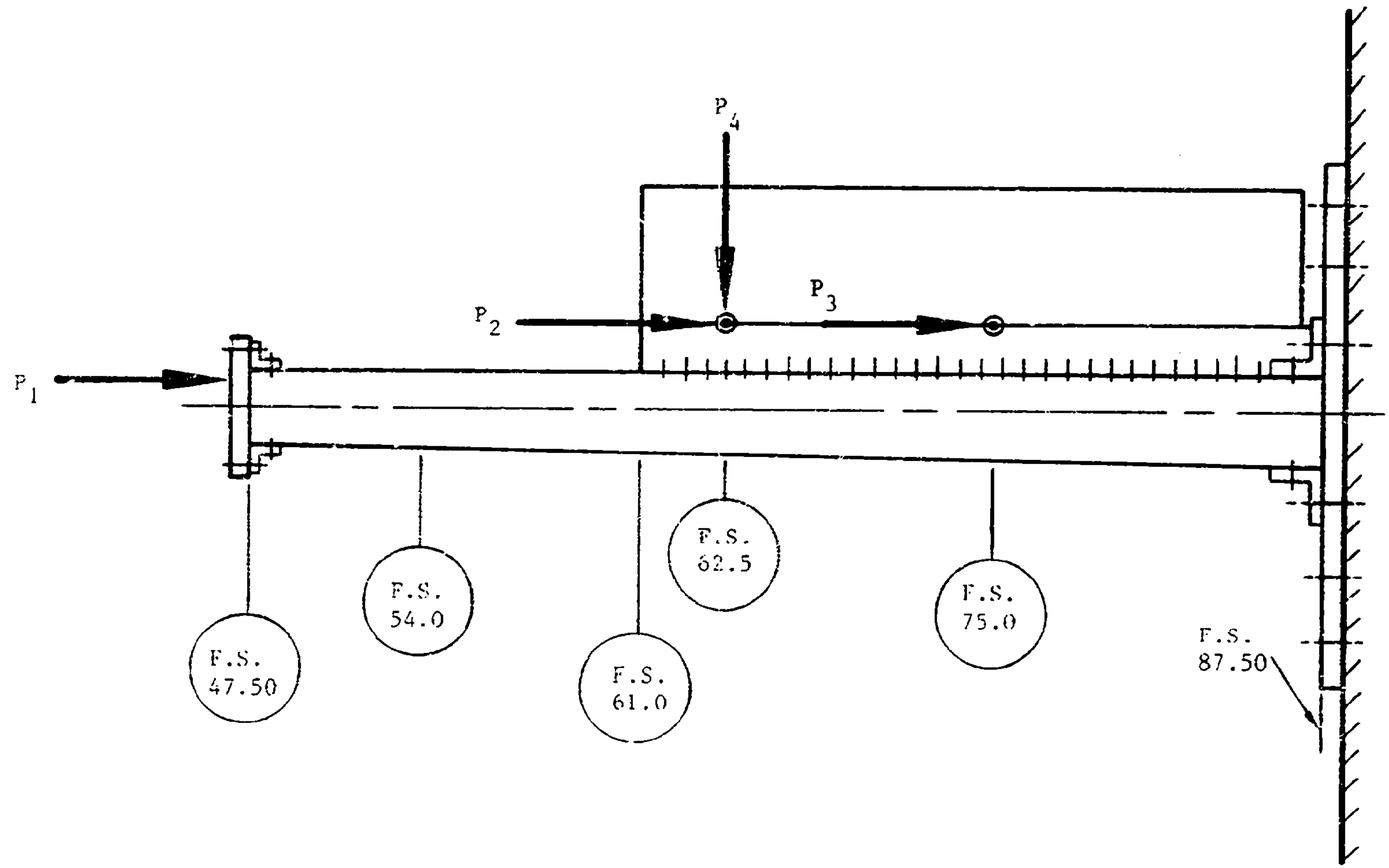

Figure 24. Avionics Deck Test Loading

P_2: This load basically offsets the moment induced tension loads of the upper skin. In addition, since this load is being applied above the deck, it also contributes to the deck bending moment.

P_3: This load has basically the same function as P_2 except it is applied at a different location. The location of this reaction (F.S. 75.00) was also selected to satisfy the deck loading.

P_4: This load basically introduces the avionics deck shear load and has a great contribution towards the deck bending moments.

The values of these loads were selected to satisfy the deck shear, moment and skin axial loads discussed before. The ultimate values of reaction loads were as follows:

P_1 = 1500 lbs

P_2 = P_3 = 1000 lbs

P_4 = 600 lbs

5.4.2 Test Setup

Since testing of the avionics deck as an integral part of the F-5F forward fuselage structure was not feasible, certain modifications were required in order to test the deck as an individual component. The lower avionics deck was set up in such a way that it simulates the actual loading of the lower deck box. An attempt was made to simulate the actual boundary conditions of the deck. Therefore, since the bending moments at the forward end (F.S. 47.50) were minimal, and much higher at the aft end (F.S. 87.50); we decided to brick-wall the deck at the aft end and leave the forward end free, as shown in Figure 24. Application of an off-center forward axial load however, would induce the forward ends required bending moment.

In addition, a plate simulating the web was attached to the upper skin of the deck in order to linearly distribute the off setting compressive reactions applied to the upper skin. The actual test setup is shown in Figure 25.

5.4.3 Static Testing

The instrumentation of the avionics deck for detecting strains was limited to strain gaging. A number of axial and rosette gages were applied on the critical locations of the waffle pan, upper skin and lower skin. The internal strain gages consisted of six rosette gages. These gages were applied by Northrop prior to the assembly and delivery of the avionics deck to the Air Force.

Prior to the initial strain survey, a non-destructive inspection (NDI) of the deck was conducted by Air Force personnel to assure there were no severe adhesive disbond and/or rivet failures prior to the testing. After the NDI, the strain survey was resumed and the actual reaction loads applied were:

P_1 = 938 lbs (Ultimate Load = 1500 lbs)

P_2 = P_3 = (Ultimate Load = $P_{3,ult}$ = 1000 lbs)

P_4 = 402 lbs (Ultimate Load = 600 lbs)

In addition to the strain values, maximum and minimum principal stresses and maximum shear stresses were calculated and recorded for the rosette gages. However, axial stresses were calculated and recorded. The highest stress value detected was -2124 psi. The recorded strain data correlated well with the results of the analysis.

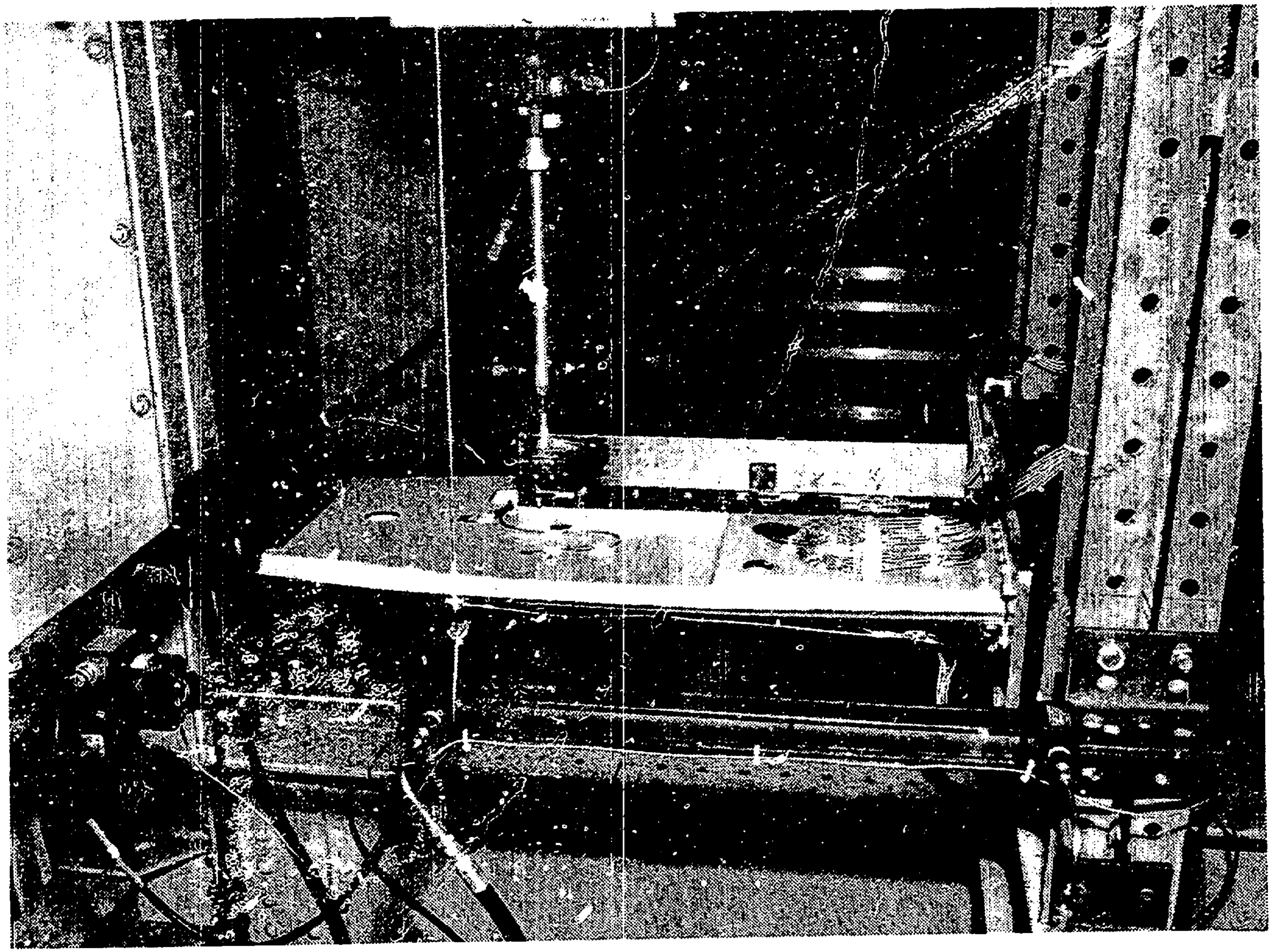

Figure 25. Avionics Deck Test Setup

The scope of the testing was to determine the room temperature loads versus strain response to limit load (2/3 of ultimate load) for two conditions, Condition I (loading check out) and Condition II (critical load condition, TAB13010). The avionics deck successfully carried the limit load without signs of any failure.

5.4.4 Fatigue Test

In order to fully verify the structural integrity of the deck and SPF aluminum, Northrop proposed fatigue testing of the SPF avionics deck. Since the avionics deck was located at the F-5F forward fuselage, which was a non-critical fatigue area, a substitute fatigue spectrum was proposed. The proposed fatigue spectrum was the F-5F dorsal longeron which has a moderately severe tension dominated spectrum. A blocked fatigue spectrum was developed to simulate the fatigue loading. The testing consisted of two life times. A typical loading represents 200 flight hours as shown in Table 7. One life time consists of 4000 hours or 20 blocks.

TABLE 7. BLOCKED SPECTRUM LOADING

BLOCK NUMBER	CYCLES	MAXIMUM LOAD (% OF LIMIT LOAD)
I	6000	65
II	120	90
III	20	110
IV	1	125

The subject fatigue schedule was designed by assuming that each life time consisted of 4000 flight hours.

The avionics deck survived four life times of fatigue loading. Subsequent to fatigue testing, the deck was subjected to static load equivalent to twice the ultimate load. No failure occurred at this load level, and there was no visible damage to the deck.

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SECTION 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

A five-phase program was carried out to exploit the applications of SPF aluminum and develop and demonstrate the process as a viable means of producing structural airframe parts that are more efficient and cost effective than conventionally produced parts.

Several aluminum alloys were evaluated for their SPF potential and Reynolds material MD254 was found to have the highest SPF potential. The post-SPF mechanical properties of this material were found to be comparable to 7075-T6 aluminum. Conceptual design studies were carried out to identify the parts which will make full use of superplastic forming. The major emphasis was on reduction of piece count and assembly costs. Two components, namely, the LEX and avionics deck were selected and redesigned as SPF assemblies.

Producibility forming tests were conducted to assess the forming feasibility of the components based on the initial design parameters. Based on the results of these tests, slight modifications were made in the original SPF design to make sure that no cavitation was formed, and minimum thickness requirements were met during the fabrication of the SPF components.

The LEX corrugation and three SPF parts (outer skin, inner skin and waffle pan) for the avionics deck were made without any scrap parts. The avionics deck was assembled using rivet bonding. The deck was tested under static and fatigue loading.

The deck was tested under static loading to design limit load and then tested under constant amplitude fatigue loading. Subsequent to two lifetimes of fatigue loading, the deck was loaded to 200 percent of the design ultimate load without failure.

6.2 CONCLUSIONS

The studies carried out in this program have resulted in the following conclusions:

(a) Designing aircraft structural parts using SPF technology can result in significant cost and weight savings.

(b) Superplastic forming of complex components may require producibility forming tests on smaller parts, simulating critical forming areas, to assure the forming feasibility of complex parts.

(c) Slight design modifications in the design of SPF parts may have to be made if the results of forming feasibility tests indicate forming problems such as cavitation in critical areas or not meeting minimum thickness requirements.

(d) Post-SPF mechanical and crack growth properties of 7475-T6 material, formed at 50 and 150 percent strain, are comparable to conventional 7475-T6 material.

(e) Adhesive bonding, resistance seam welding and weldbonding of post-SPF material do not represent any problem. The surface preparation and joining information developed for 7075-T6 material can be applied to post-SPF 7475 material.

SECTION 7

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